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Unsaturated Water Flow at the Hanford Site: A Review of Literature and Annotated Bibliography

G. W. Gee
P. R. Heller

May 1985

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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UNSATURATED WATER FLOW AT THE HANFORD SITE: A REVIEW OF LITERATURE AND ANNOTATED BIBLIOGRAPHY

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Richland, Washington 99352

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EXECUTIVE SUMMARY

As an initial part of a performance assessment task for the Hanford Waste Management Plan, we have reviewed research done over a number of years on unsaturated water flow at the Hanford site near Richland, Washington. This work will be helpful in assessing the probability that water infiltrating the ground surface may eventually contribute to ground-water recharge at the site. Reports done primarily by Atlantic Richfield Hanford, Rockwell Hanford Operations, and Pacific Northwest Laboratory were reviewed for their pertinence to unsaturated water flow and specifically for information that could help resolve the question of whether recharge of the unconfined aquifer by natural precipitation (meteoric water) is occurring on the Hanford site and, if so, what are the expected ranges of recharge.

The reports that we reviewed are primarily technical reports detailing the physical and hydrologic characteristics of soils and sediments at specific locations on the Hanford site, or describing studies that have either monitored or simulated such parameters as surface evaporation, soil moisture storage, and deep drainage (recharge). The appendix of this report provides abstracts and annotations on 24 key technical reports on subjects related to estimation of recharge at Hanford.

General conclusions from these reports can be summarized as follows:

- Water contents at depth in Hanford sediments are generally low, ranging from 2 to 7 wt% in coarse- and medium-textured sands and 7 to 15 wt% in silts. The combination of coarse-textured soil, low precipitation, and relatively deep (10 to 100 m) water table gives rise to the observed soil water contents. The low water contents tend to dominate the profile, but the soils are extremely heterogeneous; hence, soil water content is not a predictable parameter. Measurements of water content alone cannot be used to predict amounts of recharge.
- Measurements of matrix potential in deep sediments (below 10 m) in the 200 Area suggest that the water in these sediments is slowly draining to the water table. The rate of drainage depends primarily

on the unsaturated hydraulic conductivity of the sediments. Few in situ measurements of hydraulic conductivity have been made to date, but continued monitoring of injection well tests may provide in situ measurements useful for estimating unsaturated hydraulic conductivity.

- Lysimeter studies in the 200 Area from 1971 through 1977 indicated that, within the precision of the neutron probe measurements (±1% vol), the recharge could only be estimated with a precision of ±2.6 cm/yr for a given set of readings. The lysimeter data, however, suggest that water did not move below the 5-m depth over the 6-year test period. Water removal by plant extraction is a possible explanation for the low rate of recharge at this location.

- Lysimeter and field studies in the 300 Area from 1979 through 1984 indicate that water is moving at depths below the plant root-zone. Recharge rates from bare soil exceeded 5 cm/yr for the past 2 years. Estimates of recharge from a grass-covered field site ranged from 3 to 8 cm/yr. Coarse-textured soils and shallow-rooted plants, combined with above-normal precipitation, have optimized conditions for recharge at this location.

- Tritium sampling of unsaturated sediments in the 200 Area indicated that infiltrating water had moved to depths of 5 m by 1969. If steady recharge is occurring, tritium levels should have increased at depth since 1969. For example, a steady flux of 2 cm/yr would cause present-day levels of tritium in soil water to be elevated above background levels down to depths of 9 m or more. Further testing of water migration using tritium tracers is warranted.

- Model simulations have been helpful in qualitatively assessing recharge rates, but input data such as soil hydraulic parameters and actual evapotranspiration values have not been measured with sufficient accuracy to qualitatively predict recharge. Conditions exist at the Hanford site that can cause recharge to range from 0 to more than 5 cm/yr, depending on the climatic variables, topography, soil, and plant type and distribution. Models used for recharge calculations should correctly incorporate measured hydraulic conductivities, evapotranspiration rates, and effects of soil variability (layering, etc.) to correctly predict recharge rates at a given site. Tests of model performance should be conducted over the next several years using data sets that contain these inputs.

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INTRODUCTION

Virtually all of the radioactive waste on the Hanford site, near Richland, Washington, is stored near the ground surface in tanks and trenches or buried at relatively shallow depths (5 to 20 m) in the ground. The safe disposal of these wastes is a major concern of the Department of Energy (DOE), and considerable effort has been expended to ensure that waste stored and previously disposed is effectively isolated or contained. Assurance that only negligible amounts of contaminants will be leached to the ground water is a basic requirement for all waste storage and disposal at Hanford.

At Hanford, the soils are relatively coarse-textured and generally low in water content. The water table is deep enough so that, with few exceptions, buried wastes are not in direct contact with ground water. The unsaturated (vadose) zone, defined as the zone of geologic material that lies between the land surface and the permanent water table, may prove to be an ideal location for long-term storage of a wide variety of radioactive wastes on the Hanford site, particularly on the 200 Area plateau where the water table is very deep (up to 100 m). However, the suitability of the unsaturated zone for disposal of waste depends on a number of factors including present and future water balance (controlled by climate, soils, and vegetation), physical stability of the sediments (rates of wind and water erosion), and the control of human intrusion. A number of technical reports have addressed these factors to varying degrees, but a comprehensive analysis of the unsaturated zone for disposal of select wastes remains to be completed.

Pacific Northwest Laboratory (PNL) has reviewed the research on the Hanford site completed over a number of years that could be helpful in assessing water infiltration and recharge at the site. The reports that we reviewed are primarily technical reports detailing the physical and hydrologic characteristics of soils and sediments at specific locations on the Hanford site, or describing studies that have either monitored or simulated specific hydrologic processes such as surface evaporation, soil moisture storage, and deep drainage (recharge).

GENERAL CONSIDERATIONS FOR RECHARGE ESTIMATES

The flow of water through the unsaturated zone on the Hanford site has been investigated in some detail for the past 20 years. More than 20 technical reports on unsaturated water flow studies for the Hanford site are listed in the appendix. Two of these studies (Brownell et al. 1975; Gee and Kirkham 1984) draw significantly different conclusions regarding the amount of recharge that can be expected on the site. This report provides a background for the measurement and modeling of unsaturated flow at the Hanford site, describes the key studies which have attempted to measure unsaturated water flow, and suggests ways to determine how much recharge can be expected on the Hanford site. The amount of percolation or recharge can be described quantitatively if the processes that control soil water movement are understood.

NATURAL RECHARGE

Recharge to ground water can come from numerous sources including the infiltration and percolation of natural precipitation through soils; seepage from canals, streams, and reservoirs; and artificial injection through wells or surface ponding (Freeze and Cherry 1979; Hillel 1982, p. 250). After operations on the Hanford site are completed, the primary source for recharge in the waste disposal areas will be meteoric water percolating through the soils and sediments surrounding the buried waste.

Hillel (1982, p. 209) describes the movement of soil water as a continuous, cyclic sequence. The cycle begins with the entrance of water (from rain or snow melt) into the soil by the process of infiltration. This is followed by the temporary storage and redistribution of water in the soil. The cycle is completed by the removal of water from the soil by drainage, evaporation, or plant uptake (transpiration). Figure 1 shows the components of this soil-water cycle for the Hanford site. The processes of infiltration and redistribution are generally quantified by direct measurement (e.g., rain gages and soil moisture monitoring) while evapotranspiration (evaporation plus transpiration) and drainage are often obtained by indirect measurements.

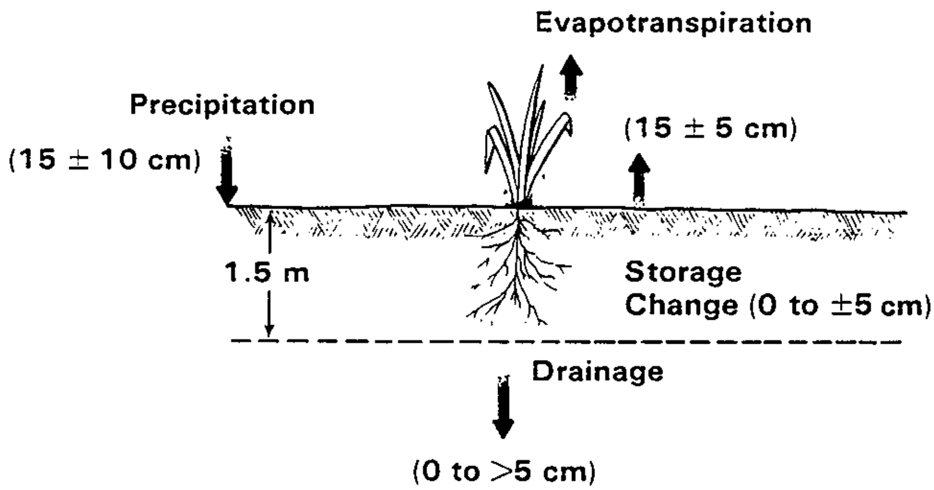


FIGURE 1. Water Balance at Hanford Area Waste Sites. Range of components in water balance equation are indicated.

Measurements of Soil Water Content by Neutron Probe

Water contents of soils can be measured conveniently using down-well measurements with neutron probes (Hillel 1982, p. 61). Estimates of evapotranspiration and drainage can be made using this method. For example, Campbell and Harris (1977) and Evans, Sammis and Cable (1981) report evapotranspiration estimated from neutron probe measurements for sites in Washington State and Arizona. By assuming a zero drainage component and using neutron-probe-measured water storage and measured precipitation, these researchers were able to estimate evapotranspiration as $ET = P - \Delta S$ where ET, P, and ΔS are evapotranspiration, precipitation, and soil moisture storage changes, respectively, measured over a given time interval (1 week or longer). In studies where deep drainage is thought to occur, neutron probe measurements also can be used to estimate drainage rates (Prill 1968; Gee and Kirkham 1984). Logging of moisture content is performed at depth as a function of time and the differences in moisture content below the root zone are used to estimate the amount of drainage. The precision of the neutron probe dictates the range of recharge rates that can be measured with this method. It also should be noted that water content changes with depth imply movement (drainage or redistribution), but that a steady or constant water content measurement does not mean that flow is zero. Soil water follows specific flow laws, which require the flow to be proportional to the energy gradient. Conditions exist where drainage in unsaturated soil occurs with no change in water content (Hillel 1982, p. 113).

Estimates Using Soil Hydraulic Properties

Table 1 lists selected hydraulic properties for a 200 Area lysimeter soil (Hsieh, Reisenauer and Brownell 1973). The water retention data suggest that the soil is a relatively uniform sand with few fines (material less than 63 μm). Based on the water retention data and the calculated hydraulic conductivity values, it is apparent that a wide range of flow conditions can exist even in relatively dry sediments (see also Jones 1978). Table 1 shows that water flow rate can vary as much as two orders of magnitude (from 0.005 to 0.5 cm/yr) as water contents vary only a few percent (from 5% to 7%). Note that for these coarse-textured sediments a relatively large change in matric potential from -1 to -15 bars occurs over a range of about 1% water content (Routson and Fecht 1979; Heller, Gee and Myers 1985 and Table 1). These data suggest that at matric potentials[a] typical of well-drained or relatively dry soils (-0.3 to -3.0 bars), water flow by drainage processes would be in the range of a few millimeters a year or less. Because soil characteristics depend on texture (Routson and Fecht 1981; Heller, Gee and Myers 1985), no single set of water retention and hydraulic conductivity data can be used to predict drainage rates; however, for most of the sandy-textured Hanford sediments,

---

(a) Matric potential is a measure of how tightly water is held in soil. The lower (more negative) the matric potential, the more energy required to remove water from soil. Rigorously defined, matric potential is the free energy of soil water with respect to the free energy of pure water measured at atmospheric pressure and at the same elevation and temperature as that of the soil water (Hillel 1982, p. 69). Expressed as energy/mass, the units for matric potential are joules/kilogram; as energy/volume the units are pressure units (i.e., newtons/m^2, bars or atmospheres); as energy/weight, the units are head units (i.e., meters, centimeters, or feet). The term matric implies that the energy state of soil water is affected by the entire soil matrix including the soil pores and particle surfaces.

TABLE 1. Relationship of Soil Water Contents to Matric Potential and Hydraulic Conductivity for 200 Area Lysimeter Soil (Hsieh, Brownell and Reisenauer 1973)

Water Content (vol%)	Matric Potential (-bars)	Hydraulic Conductivity (cm/min)	(cm/yr)
10.0	0.1	4×10^{-5}	2×10^{1}
7.0	0.3	1×10^{-6}	5×10^{-1}
5.5	1.0	1×10^{-7}	5×10^{-2}
5.0	3.0	1×10^{-8}	5×10^{-3}
4.3	15.0	8×10^{-10}	4×10^{-4}

water contents between 4 and 8 volume percent (vol%) appear to represent 'field capacity' (i.e., moisture contents for these soils at which the majority of free (rapid) drainage has taken place).

CLIMATE/PRECIPITATION

Precipitation in the form of rainfall and snow melt is the source for natural recharge on the Hanford site. Climate variables including rainfall/snow distribution, temperature, wind speed, and solar radiation coupled with soil and plant factors control the amount of water that is available for recharge. The climate on the Hanford site is semiarid with annual precipitation at the waste sites averaging 16 cm/yr (as measured at the Hanford Meterological Tower in the 200 Area). The summers are hot and dry and winters cool and moist. Most precipitation falls during the winter months. Almost half (48%) falls between October and January, while only about 10% falls during the months of July, August, and September (Stone et al. 1983). Thus, precipitation is least when the potential for evapotranspiration is greatest, and precipitation is largest when evapotranspiration is least.

Using general water balance considerations, assuming average annual precipitation (P) and estimates of potential evapotranspiration (PET), Summers and Deju (1974) and Deju and Fecht (1979) have calculated that the Hanford site (200 and 300 Areas) has an annual water deficit (PET-P) in excess of 100 cm. They speculate from this that natural recharge in the 200 and 300 Areas is essentially zero (not measurable) and suggest that water is lost to the atmosphere from the soil before deep penetration can occur. However, since almost half of the annual precipitation occurs during the winter when the potential evapotranspiration is low, recharge conditions are favored. The amount of winter precipitation that moves below the plant root-zone and is lost to deep percolation can only be determined by a careful analysis of the entire climate-soil-plant system, and the time dependence of the interactions within this system. This type of analysis has only been recently undertaken at the Hanford site (Gee and Kirkham 1984).

PLANTS

The major plant communities common to waste burial areas on the Hanford site have been well documented (ERDA 1975; Brown and Isaacson 1977). In the 200 and 300 Areas, the predominant vegetative cover consists of sagebrush (*Artemisia tridentata*) and cheatgrass (*Bromus tectorum* L.). Other shrubs and grasses in these areas include rabbitbrush, (*Chrysothamnus nauseosus*), bitterbrush (*Purshia tridentata*), and Sandberg bluegrass (*Poa sandbergii*).

The sagebrush-bitterbrush/cheatgrass vegetation-type plant community under natural conditions grows extensively on the sandiest soils at Hanford, particularly in the 300 Area. This plant community is subject to major disturbances at or near waste sites in the 200 and 300 Areas. Both natural brush fires and construction operations have removed significant portions of the deeper rooted sagebrush and bitterbrush at these waste sites. The recent fire of August 12, 1984, which burned over 800 km^2, is an example of how quickly and completely large areas of sagebrush on the Hanford site can be destroyed.

An efficient early invader of burned and disturbed areas is tumbleweed (*Salsola kali* L.). Tumbleweed has an effective method of seed dispersal, through wind-carried plants and seeds in the fall and winter. Tumbleweed is not as competitive as cheatgrass, but it can successfully invade where cheatgrass is suppressed by mechanical means or herbicides, or in soils with hetereogeneous textures (ERDA 1975). In time, cheatgrass and tumbleweed will tend to become dominant in the 200 and 300 Areas as more soil is disturbed by construction of waste burial sites and associated facilities, and the slower growing, deeper rooted shrubs are removed.

Cline, Gano and Rogers (1980) have indicated that most of the disposal site areas at Hanford have developed irregular stands of cheatgrass, Russian thistle (tumbleweed), and gray rabbitbrush with variable rooting depths. These three plants have all been observed to remove radioactive elements from the soil and concentrate them in plant tissue (Selders 1950; Schreckhise and Cline 1979).

Measurements of rooting depths have been made for both shrubs and grasses under burial ground and disturbed area conditions at Hanford. Klepper et al. (1979) found rabbitbrush roots at 2.2-m depth in the 200 Areas (near the 216-A-24 Crib). Cline, Gano and Rogers (1980) found that Russian thistle roots penetrated below 2.4 m at a simulated trench plot in the 200 Area. Gee and Kirkham (1984) measured cheatgrass roots to depth of less than 1 m at a burned-over site in the 300 Area. A recent report (Klepper, Gano, and Cadwell (1985) provides even more detail on rooting densities and distributions of deep-rooted shrubs under the Hanford site (200 Area) conditions. At two sites located adjacent to the 200-E and 200-W Areas, antelope bitterbrush (*Purshia tridentata*) and sagebrush were found to have the deepest roots, averaging depths of 3.0 m and 2.0 m, respectively. Depth of root penetration is a plant characteristic that can be modified by soil physical properties and rainfall, and hence will be very site specific.

Hydrologic Consideration

Plants evaporate water from their leaf and stem surfaces (transpiration). The areal extent of the plant cover expressed as a leaf area index (LAI) or in a more general sense, the percent ground cover, is an important consideration in determining the transpiration rate from a given area (Hillel 1982, p. 291). Estimates of leaf area, percent cover or direct measurements of transpiration are needed as inputs to models which simulate water balance at arid sites. Little information is available on quantitative measurements of evapotranspiration at the Hanford site, but this information will be required for water balance model testing and model validation purposes (Gee and Kirkham 1984).

Data on root distributions and densities, under specific waste site conditions, are needed to estimate depth and extents of water withdrawal by plants. Such measurements for the Hanford site are limited (Cline, Uresk and Rickard 1977; Klepper, Gano and Cadwell 1985). Additional information on expected plant revegetation type(s), soil characteristics and climatic variables (precipitation, etc.) will be needed to accurately predict water withdrawal and root-zone water storage at a given waste site at Hanford.

SOILS/SEDIMENTS

Soils and sediments at Hanford have been investigated extensively from geomorphic as well as physical and chemical considerations. Three distinct sediment types have been identified for the Hanford site area (Newcomb, Strand and Frank 1972; Brown 1959; Brown 1970a).

Ringold Formation

The Ringold Formation consists of silts and clays topped with occasionally cemented sands and gravels and fine sands. The lower portion of the Ringold Formation generally conforms with the surface of the underlying basalt bedrock. The thickness of this layer is a function of position at the Hanford site. The water table is usually found in or just above this formation.

Hanford Formation

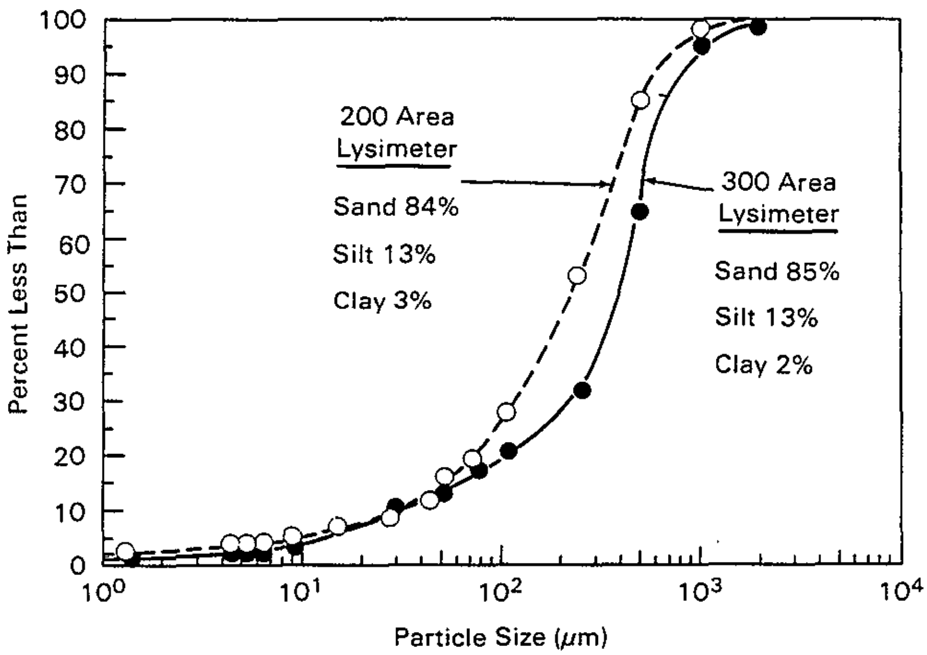
Most of the soils and sediments that occur above the Ringold Formation and the basalt (bedrock) at the Hanford site accumulated as a result of catastrophic floods at the close of the Pleistocene Epoch (~12,000 years ago). These floods deposited thick sequences of glaciofluvial sediments (coarse gravels and sands sparsely mixed with thin layers of silt). In the 200 Area, these sediments are nearly 100 m thick. In the 300 Area, they are 10 to 15 m in thickness. These sediments are sometimes referred to as the Pasco gravels (Brown and Isaacson 1977) and generally dominate the lithclogical sequence of the unsaturated zone.

Eolian Deposits

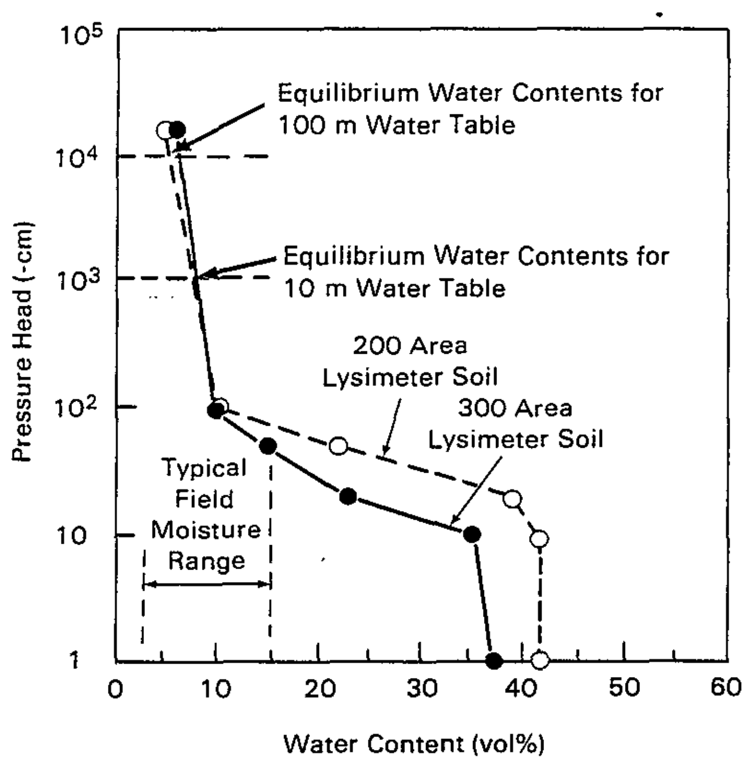
Loess and sand dunes mantle the surface of the Hanford site. These deposits are primarily reworked sediment of the Hanford Formation from surrounding areas. The thickness of the wind-blown sediment varies considerably, ranging from 0 to more than 20 m in some areas.

Hydrologic Considerations

Because most of the unsaturated zone sediments are water-laid sediments, some inferences can be made about the water status of these materials. During and soon after the catastrophic flooding, these materials were saturated. Some time after the floods subsided, these materials drained; hence, the water contents of the lower layers (not subject to surface evaporation) should reflect a drained soil condition. Estimates of flow (drainage) can be made by looking at the water content and water potential relationships of the soil. If one assumes that there are either zero flow or very low flow rates, then the observed water contents in the Hanford sediments should reflect a drained, layered, soil whose water potential distribution could be considered to be in equilibrium or near equilibrium with the water table. Then, water contents can be estimated from curves similar to Figure 2. In the 200 Area where the water table is approximately 100 m deep, the soil at equilibrium with the water table will have a water content that corresponds to a matric water potential (expressed as energy/weight) equal to the height above the water table. Water release (retention) curves have been measured on a number of sediments at Hanford. Figures 2a and 2b show particle-size distribution and the water retention characteristics, respectively, of the sand fraction of Hanford Formation sediments found in the 200 and 300 Areas. Based on these curves, one can estimate that at equilibrium, the water contents of these coarse sediments above a 100-m water table should range from 5 to 7 vol% over much of the profile (Figure 2b). Coarser materials (gravels) often found at depth in the 200 and 300 Areas would have lower water contents, ranging from 2 to 4 vol%. The Ringold silts that generally occur near the water table have drained water contents ranging from 10 to 15 vol%.



2a. Particle-Size Distribution



2b. Water Retention Characteristics

FIGURE 2. Particle-Size Distribution and Water Retention Characteristics of Soils from the 200 and 300 Area Lysimeters at the Hanford Site

Reports by McHenry (1957), Brownell (1971), Fecht, Last and Marratt (1978), Fecht, Last and Marratt (1979), Routson and Fecht (1979), Isaacson (1982). Heller, Gee and Myers (1985) have provided detail on the heterogeneities present in Hanford sediments that give rise to observed variable moisture contents. The variation in field moisture content is largely a result of sediment textural variations (e.g., layers and mixtures of coarse and fine sands, gravels and silts). Until recently, only a few reports detailed direct measurement of field moisture. Brownell (1971) and Routson and Fecht (1979) report field moistures ranging from 1 to 5 wt%, but qualify the data by indicating that sample dessication may have occurred. In a recent study, Heller, Gee and Myers (1985) collected a series of moisture samples from five corings near the Wye Barricade (located between the 200 and 300 Areas below the 200 Area plateau). The data from one borehole are shown in Figure 3. These data indicate that the field soil (ranging in water content from 4 to 8 wt%) is consistently as wet or wetter than laboratory samples taken from this same borehole and equilibrated at 0.1 bar and 1.0 bar pressure on a conventional pressure plate. These data suggest that field moisture content at this site is sufficiently high that drainage is likely occurring from this site. Although the drainage rate cannot be determined from these data without knowing the hydraulic conductivity of the soil, the data in Figure 3 provide evidence that the unsaturated sediments are far from equilibrium with the water table and are draining.

If certain assumptions are made about the relationship of the water content and the hydraulic conductivity, estimates can be made of expected recharge rates under steady flow conditions. Conversely, if certain recharge rates are assumed then there should be unique water contents that exist under given recharge rates. In a preliminary study of this methodology, Heller, Gee and Myers (1985) show that, if recharge rates of 0.5 and 5.0 cm/yr are assumed, the expected average water contents for a given borehole range from 5 to 7 wt% in keeping with the observed water contents. An analysis should be undertaken to investigate this prediction capability to estimate recharge rates from moisture contents. To test this methodology, measurements of in situ hydraulic conductivity values would be required for the draining sediments.

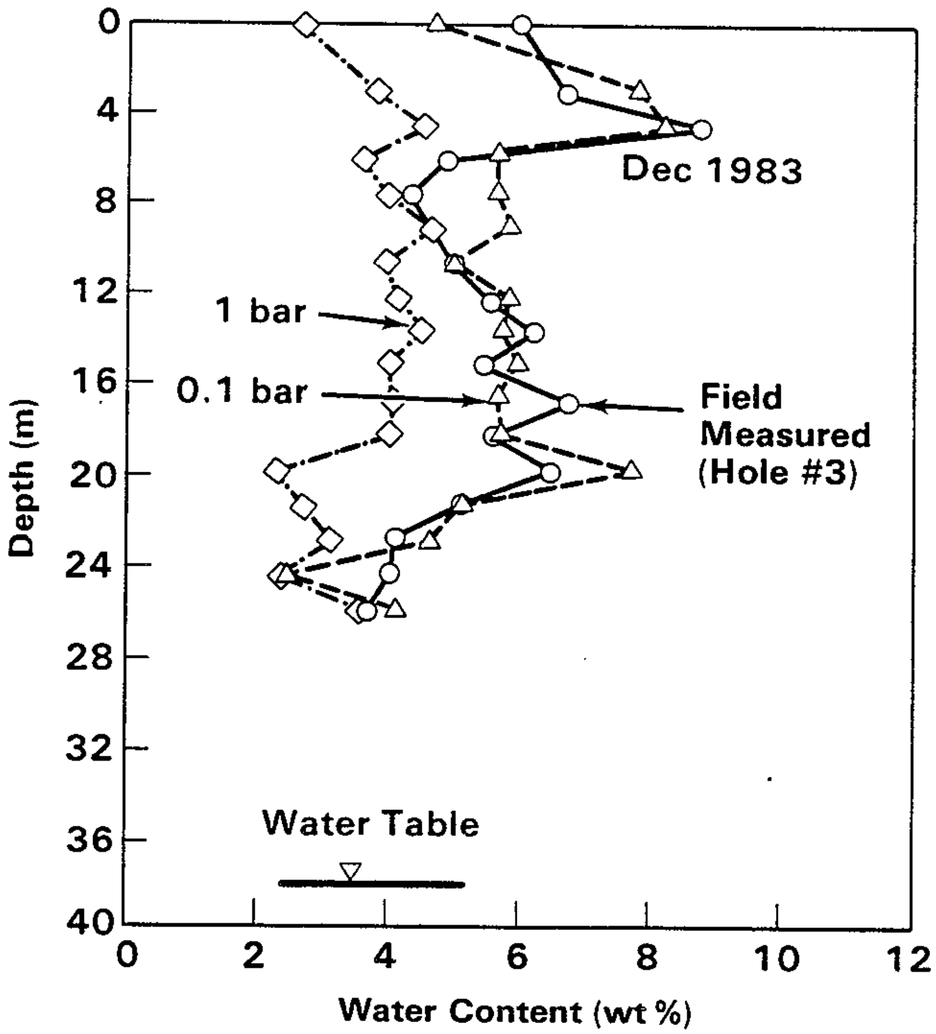


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FIGURE 3. Field-Measured Water Contents and Laboratory-Measured Water Retention (0.1 bar and 1.0 bar pressure tests) for Sediments Cored Near the Hanford Wye Barricade

RECHARGE AND WATER BALANCE STUDIES

The combination of climate, plants, and soils dictate the water balance at any given site. Amounts of recharge under arid site conditions are seldom measured directly. The recharge estimate or calculation is usually indirect and uncertainties in the measurements of other components of the water balance are often large (Evans, Sammis and Cable 1981; Sammis, Evans and Warrick 1982). Even under irrigated conditions, large uncertainties exist. Using three different techniques (Darcy flux/hydraulic gradient calculations, thermal flux estimates, and tritium tracer tests), Sammis, Evans and Warrick (1982) estimated deep percolation rates from irrigated land near Phoenix, Arizona. The estimates ranged from 9 to 40 cm/yr depending on the method of measurement. These authors caution against using a water balance approach (estimating recharge as the difference between applied water and evapotranspiration) because most estimates of annual evapotranspiration (ET) can have large errors (±50% or more). These uncertainties are compounded when the water balance approach is used to estimate recharge under arid site, nonirrigated conditions, because the inputs are less and the methodologies currently available for estimating ET work well only for irrigated crops. Aside from direct measurement using weighing lysimeters (to be discussed later) there appears to be no direct way to measure annual ET for desert plants, hence recharge estimates under these conditions are extremely limited. Several methods have been used at the Hanford site to estimate recharge. These include monitoring of matric potential gradients in deep wells, lysimetry for water balance and direct measurement of drainage, and tritium profile monitoring. These experiments will be discussed in turn.

DEEP WELL TEST

One of the most innovative tests ever devised to estimate recharge above a deep water table was initiated at Hanford in 1969 (Enfield, Hsieh and Warrick 1973; Brownell et al. 1975). This test, sometimes referred to as the Thermocouple Psychrometer Experiment, was performed at a site on the 200 Area plateau, about 1 km southeast of the 200-E area. In this test, a string of instruments including temperature sensors and thermocouple psychrometers[a] were inserted in an encased well and the well was backfilled with sediments taken from the well. First year results were reported by Enfield, Hsieh and Warrick (1973). Although some of the psychrometers failed over time, data for about a 4-year period were collected and the results reported by Brownell et al. (1975).

Figure 4 shows a plot of matric potential with depth at the 32-49D well. The interpretation of these data has been that a desiccated (dry) zone persists at depths of 5 to 10 m, and that this desiccated zone prevents recharge from occurring (Brownell et al. 1975). Another interpretation is also possible. The dashed line in Figure 4 represents the equilibrium matric potential that should exist if the entire unsaturated zone were in equilibrium with the water table (Koorevaar, Menelik and Dirksen 1983, p. 144-148). For steady flow conditions, data to the right of the dashed line represent matric potential values that reflect evaporation and upward flow, while data to the left of the dashed line reflect drainage. The data indicate that the profile is draining. The rate of drainage (or recharge) is not known because the in situ hydraulic conductivities of the layered sediments are not known. Unsaturated hydraulic conductivities estimated from laboratory suggest that measurements (Hsieh, Enfield and Warrick 1973; and Hsieh and Enfield 1974) the recharge rate could vary between 0.3 to 1 cm/yr depending on the estimated hydraulic conductivity, depth, and corresponding matric potential gradient. Also, vapor transport was estimated using the measured temperature gradient and assuming that an enhanced vapor flow could occur, which tended to transport water to the surface in response to the decreasing temperature (Philip and deVries 1957). We have reanalyzed the data in Figure 4 using the assumptions that 1) below 10 m, the soil is not affected by surface evapotranspiration processes and 2) the matric potential is linear with depth and may have a bias of ±0.5 bars

(a) Thermocouple psychrometers are used to measure the vapor pressure (humidity) of the soil air (Hillel 1982, p. 84). At thermal equilibrium the soil humidity can be related directly to the matric potential of the soil water for soils whose soil solution is relatively salt free (i.e., the osmotic pressure of the soil solution is less than 0.2 to 0.3 bars).

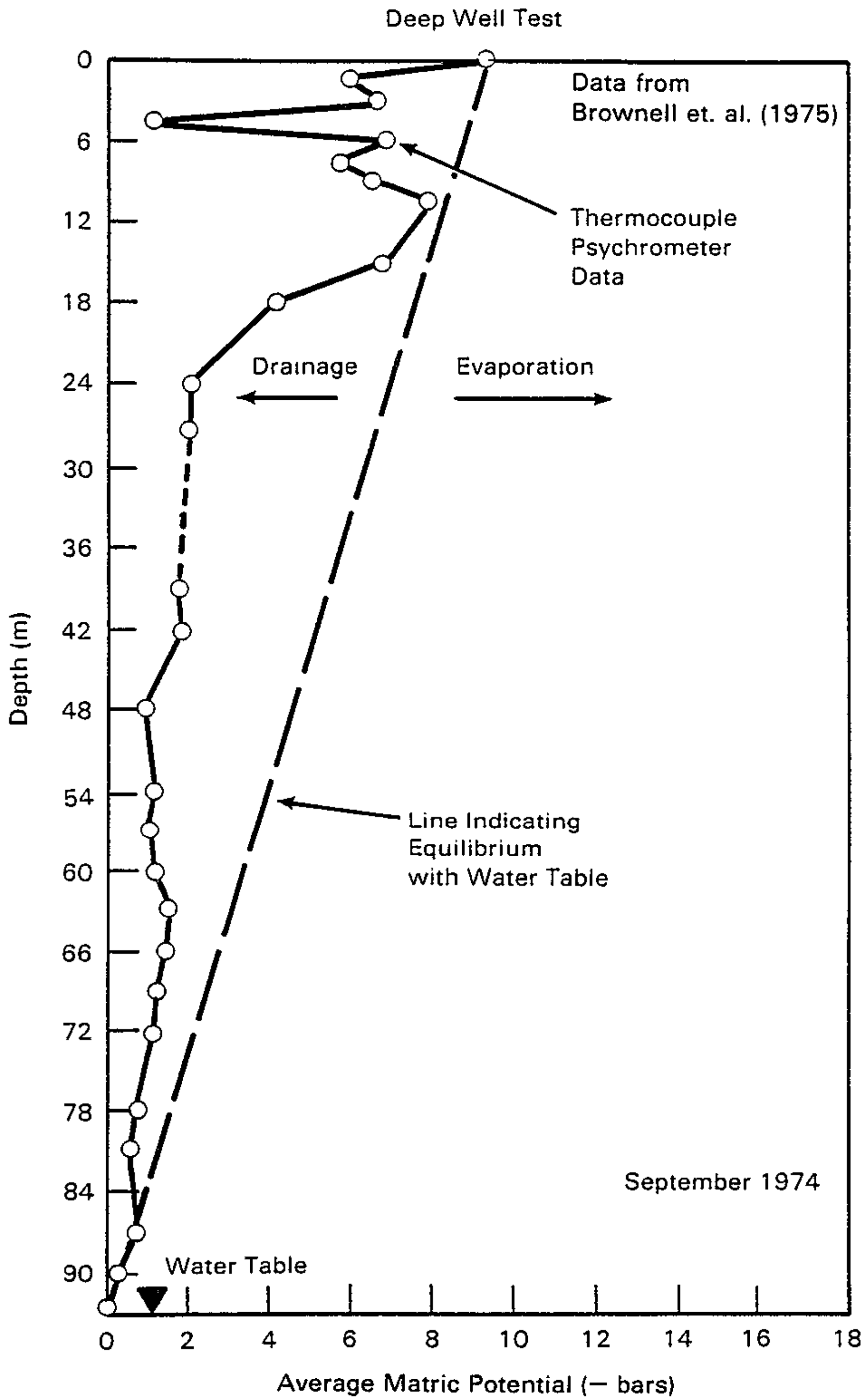


FIGURE 4. Matric Potential Profile at the Hanford Site Deep Well Test, September 1974

in the absolute values of the matric potential. Using these values, three matric potential gradients are determined from the data. Table 2 presents the recharge rates calculated from these data for three assumed values of the hydraulic conductivity. The data suggest that drainage is occurring at this site, but it is apparent that a wide range of values can be obtained with a relatively large uncertainty persisting because of the unknown in situ hydraulic conductivities. Clearly, it is important that additional emphasis be placed on determining unsaturated hydraulic conductivity in place.

We should also consider that these data represent only one location on the Hanford site. The spatial variability of sediments and layering is well documented; therefore, conclusions based on data from one location should be questioned as to whether the data represent the conditions that persist over the waste site areas at Hanford. The type of installation for sampling, however,

TABLE 2. Calculated Recharge Rates from Matric Potential Gradients and Estimated Hydraulic Conductivities at Deep Well Test Site, September 1974

Depth (m)	Matric Potential Gradient[a] (bars/m)	Total Head Gradient (m/m)	Hydraulic Conductivity (cm/yr)	Recharge Rate (cm/yr)
50	0.017	-0.83	5×10^{-2}	4.2×10^{-2}
	0.031	-0.69		3.4×10^{-2}
	0.048	-0.51		2.6×10^{-2}
	0.017	-0.83	5×10^{-1}	4.2×10^{-1}
	0.031	-0.69		3.4×10^{-1}
	0.048	-0.51		2.6×10^{-1}
	0.017	-0.83	5×10^{0}	4.2
	0.031	-0.69		3.4
	0.048	-0.51		2.6

(a) Assumes an error of ±0.5 bars in the 50-m depth reading.

is expensive, and extensive replication of instrumented deep wells will probably not be considered in future research efforts.

A major drawback to the deep well facility is the inability to retrieve and repair the instruments after they have been inserted in the ground. Thermocouple psychrometers are notorious for not maintaining calibration, and their operational life is unknown but usually short (Brown 1970b; Dalton and Rawlins 1968; Daniel, Hamilton and Olsen 1979). Failure of the units after 1 year is not uncommon. Improved electronic readout devices (providing stability and detection in the nanovolt range) have been developed during the past 15 years, but longevity of the psychrometer and its ability to maintain calibration for extended periods of time have not been established. Commercially available soil psychometers used for this type of measurement are made by only a few suppliers (e.g., Wescor, Inc., Logan, Utah; J. D. Merrill, Inc., Logan, Utah) and no lifetime is specified for the instrument.

Because the instrument does not measure humidity directly and must be calibrated (usually by a laboratory procedure using salt solutions of known humidity), the ability of the instrument to maintain calibration after a period of time in a known environment must be determined. One way to provide some confidence for the data set would be to bury a statistically sufficient number of psychrometers in a retrievable manner at a relatively shallow depth and repeatedly check the calibration on them to ensure that they maintain calibration within acceptable limits. This calibration facility could be located near a deep well facility where new psychrometers would be buried permanently.

In summary, matric potential gradient data from the deep well test strongly suggest that drainage (recharge) conditions persist at depths below 25 m. Since the in situ hydraulic conductivity of these sediments have not been measured, the recharge rate is unknown. Estimated hydraulic conductivities from Table 2 suggest that recharge rates can range from 0.03 to 4 cm/yr. Also, the uncertainty in the calibration of the thermocouple psychrometers used to measure the matric potential puts into question the reliability of the potential gradient estimates. Future tests using this type of instrumented deep well should also provide some way to estimate the stability of the psychrometers.

9 3 1 2 1 6 2 1 4 1 7

LYSIMETER STUDIES

Lysimeters are isolated, soil-filled containers used in hydrology to determine water storage changes, including evaporation and drainage (Hillel 1982, p. 296). They can range in size and configuration from a small column of soil, a few centimeters in diameter and a few centimeters deep (Boast and Robertson 1982), to large volumes of soil, several meters in diameter and 1 to 18 m deep (Harrold and Dreibelbis 1958; Pruitt and Angus 1960; Hsieh, Brownell and Reisenauer 1973). The most complete and efficient lysimeters are those equipped with a weighing device and a drainage system, which allows direct and continuous measurements of both evaporation and drainage (Pruitt and Angus 1960; Van Bavel and Myers 1962; Black, Thurtell and Tanner 1968; Kirkham, Gee and Jones 1984). The discussion that follows describes both weighing and nonweighing lysimeters used to measure drainage and water balance on the Hanford site.

200 Area Lysimeters

During late fall of 1971 and early spring of 1972 two large (18 m deep by 3 m wide) nonweighing lysimeters were constructed just south of the 200-E Area at the Hanford site (Hsieh, Reisenauer and Brownell 1973). Figure 5 shows the location of these lysimeters. The lysimeters are about 100 m northwest of well 32-49D (Deep Well Test). The purpose of this installation was to monitor water migration in the unsaturated zone under natural precipitation conditions and to evaluate the potential for recharge at Hanford. During the past 10 years, several comprehensive reports have been compiled that document the major findings from the first 6 years of data collection at this facility (Brownell et al. 1975; Last, Easley and Brown 1976; Jones 1978). Figure 5 shows a cross section of the completed facility. As indicated, one of the lysimeters was closed (sealed) at the bottom while the other was left open.

The lysimeters were instrumented with neutron probe access tubes (for moisture content) thermocouples (for temperature), thermocouple psychrometers (for soil matric potential), and stainless steel tubing for monitoring soil gas pressure. Figure 6 shows the surface of the closed bottom lysimeter in February 1974, and Figure 7 shows the surface of the open bottom lysimeter in May 1978. Because of some difficulties in getting the instrument shelter

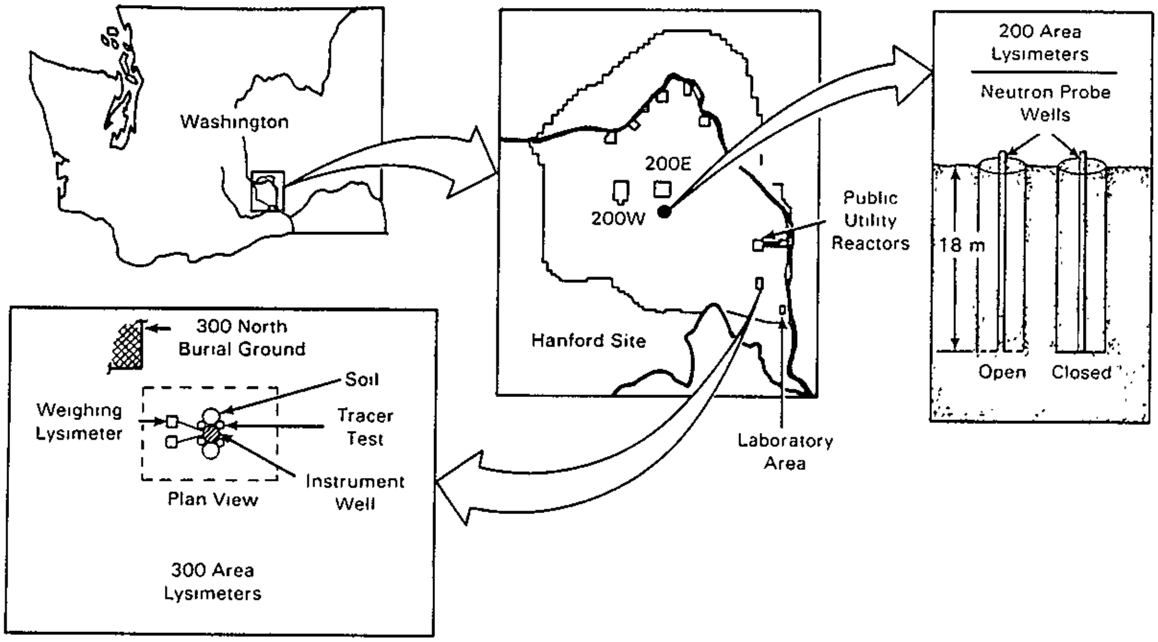
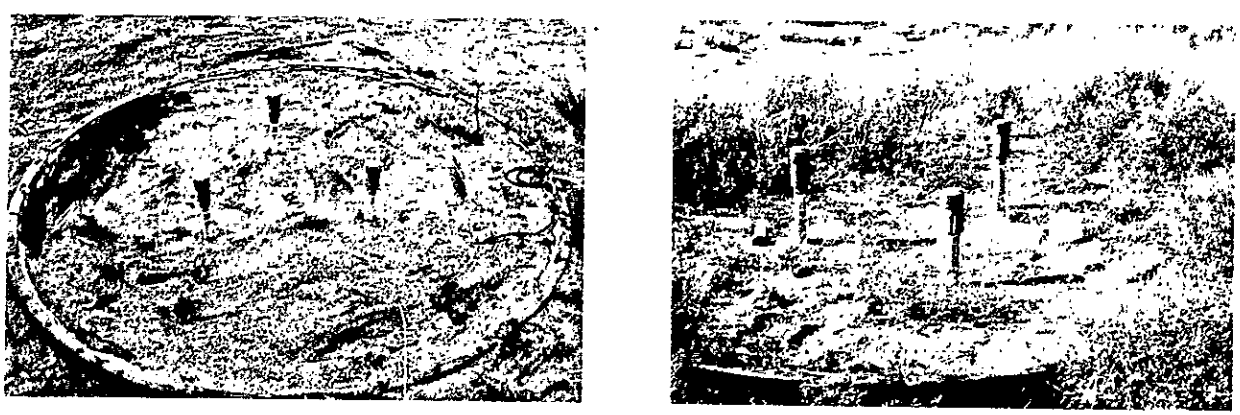


FIGURE 5. Lysimeter Locations at the Hanford Site



(a) (b)

FIGURE 6. Lysimeter Surface, 200 Area Open-Bottom Lysimeter. Tubes in center are neutron probe access wells. a) February 1974--Surface bare except for one small Russian thistle. b) May 1978--Shows significant increase in vegetation cover.

FIGURE 7. Lysimeter Site 200 Area, May 1978. Closed-bottom lysimeter in foreground. Plants growing on and adjacent to lysimeter are primarily Russian thistle.

completed, the thermocouple and thermocouple psychrometer data were not taken after 1974. The data available for this site consist of some temperature profile data taken in 1974 and neutron probe moisture content logs taken over a period of about 6 years. Three unpublished neutron-probe-logs taken from this facility in 1983 and 1984 have been made available to us recently, and we are in the process of analyzing them. (In the spring of 1983 the open-bottom lysimeter was partially decommissioned by the removal of the top 6 m of soil. No moisture probe data have been available from this lysimeter since that time.)

These data and the data taken previously (1977 and earlier) suggest that if water is draining at this site, it is draining very slowly. We have calculated rates of downward migration (recharge) that could occur at this site ranging from 0.3 to 3.0 cm/yr (Table 3). One of the difficulties in doing a

TABLE 3. Estimates of Recharge from 200 Area Closed-Bottom Lysimeter

Date	Average Water Content (5-m to 18-m depth) (vol%)	Computed Recharge since 3/72 (cm/yr)
3/72	5.7	--
9/73	5.8	0.7
1/74	6.2	3.0
9/76	5.8	0.3
8/77	6.1	0.9

quantitative analysis of recharge at this site, as pointed out by Jones (1978), is the uncertainty in the neutron probe measurements and lack of measurements of hydraulic conductivity.

Table 3 lists the measured water storage changes below the 5-m depth that occurred from 1973 to 1977 and the calculated annual recharge that can be obtained from those data. If the error in water storage estimated by neutron probe measurements is ±0.5 cm, then the average flux rate through 1977 varies between zero and approximately 1 cm/yr.

Moisture storage determined by neutron probe data is highly dependent on the calibration used in the measurement. Absolute errors of 1 to 2 vol% can be obtained when different neutron probes with independent calibrations are used to determine moisture profiles. An example of this uncertainty is illustrated in the reported data for the 200 Area lysimeters (Hsieh, Brownell and Reisenauer 1973; Brownell et al. 1975; Jones 1978). The neutron probe calibrations given in these reports do not compare well with each other, and it is difficult to assess from the reports the number of different neutron probes that were used over the 5-year test period. However, it is possible to cross calibrate these probes so that, over a given range of interest, the agreement between probes is within ±1 vol% water content (Jones 1978). An absolute error of ±1 vol% water content for water content changes over the depths of 5 to 18 m during the 6-year study period produces an uncertainty in the estimated rate of water storage change of ±2.6 cm/yr.

Further work at this facility to evaluate recharge will need to carefully address the precision, repeatability, and continuity of the neutron probe measurements.

300 Area Lysimeters

In 1978 soil-filled lysimeters were installed in the 300 Area by PNL personnel (Phillips et al. 1979). The purpose of this installation was to develop methodologies for measurement and modeling of unsaturated water flow and radionuclide transport at arid sites (Gee and Campbell 1980; Gee et al. 1981; Jones and Gee 1984). Figures 5 and 8 show a plan view and cross section of the lysimeter facility which consists of two large 3-m-diameter x 7.6-m-long cylindrical culverts (caissions) and four smaller (0.6-m-diameter x 7.6-m-deep) caissons placed around a central instrument caisson. Two small (1.5 x 1.5 x 1.5 m) lysimeters were also installed to make measurements of evaporation and drainage by direct weighing. The hydraulic and thermal properties of the soil used in these lysimeters were thoroughly measured (Cass, Campbell and Jones 1981).

In this facility drainage is measured directly in the weighing lysimeters and in the deep lysimeters by collecting and recording the amounts of water that have collected at the bottom of these lysimeters (Jones and Gee 1984; Kirkham, Gee and Jones 1984; Gee and Kirkham 1984). Measurable quantities of water have been collected routinely from both weighing lysimeters since 1979 and from one large, deep, lysimeter (South Caisson) since 1981. The total amounts of drainage that have occurred in these lysimeters since drainage was first observed are indicated in Table 4. Note that some leakage was observed in the two weighing lysimeters, so the data represent a minimum amount of water that has drained to the bottom of the lysimeters. All lysimeter surfaces were kept bare except for the south weighing lysimeter where cheatgrass was transplanted in March 1983. Several years of growth will likely be needed to ensure that the roots are well established and extracting water at their optimum. However, drainage has continued from the south weighing lysimeter that has been vegetated for the past 20 months (Gee and Kirkham 1984). As noted earlier, the past 5 years have all had above normal precipitation, with 1983 having a total of 28 cm (the third highest on record).

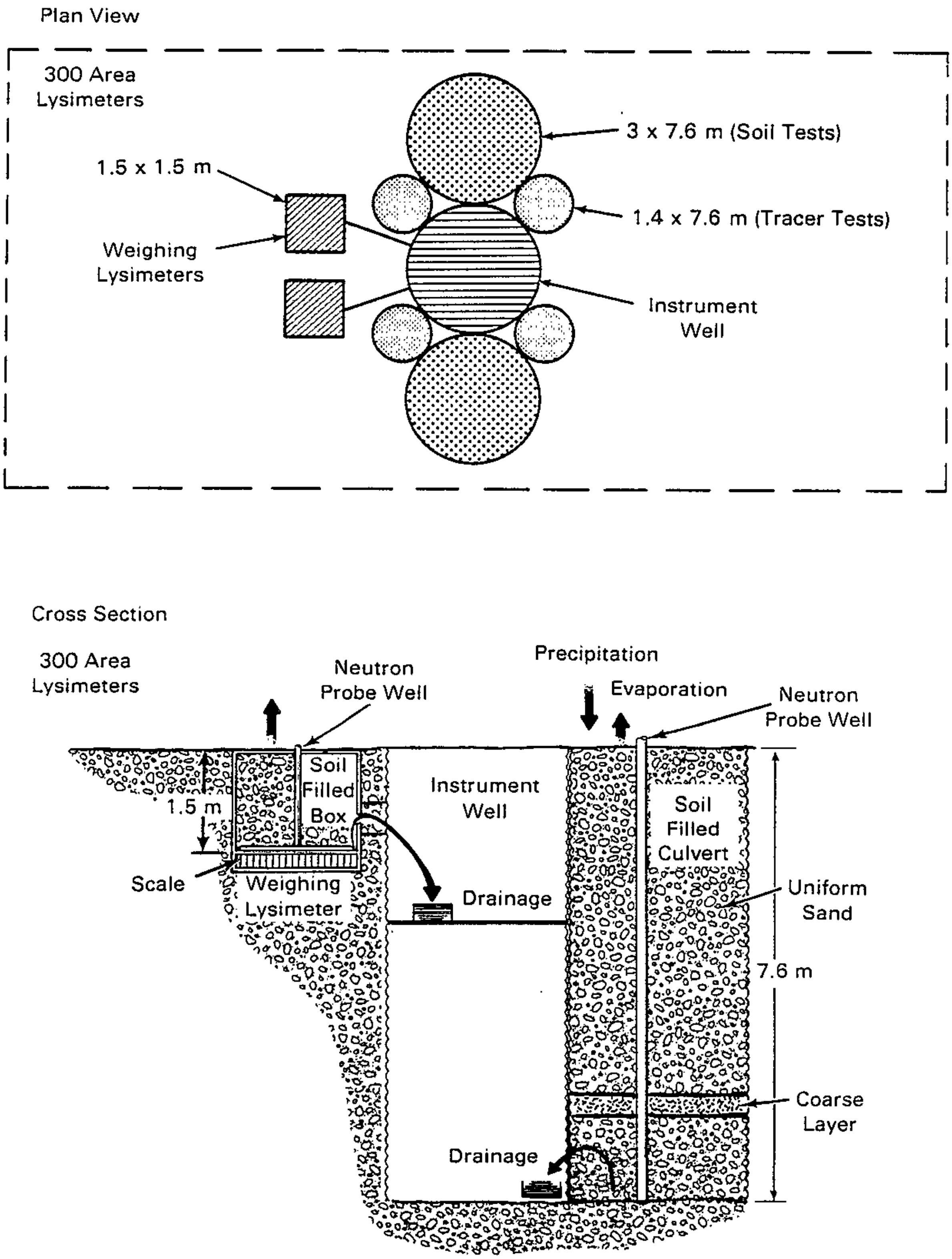


FIGURE 8. 300 Area Lysimeter Facility

TABLE 4. Measured Drainage from Bottom of 300 Area Lysimeters

Year	Lysimeter	Recharge Rate (cm/yr)
1980	North Weighing (irrigated, 65 cm)	23.4
	South Weighing (nonirrigated)	1.1
1981	North Weighing (irrigated, 7.9 cm)	6.8
	South Weighing	1.5
	South Caisson	1.1
1982	North Weighing	5.3
	South Weighing	3.2
	South Caisson	5.6

These data strongly support the concept that drainage can occur on the Hanford site under conditions where surface soils are coarse and major precipitation events occur during periods of low potential evapotranspiration. The water uptake by deep-rooted plants on the Hanford site has never been quantified, but such a study should be undertaken to more thoroughly evaluate the effect of deep-rooted annuals on the actual evapotranspiration under Hanford site conditions. The placement of a sagebrush plant into a weighing lysimeter could provide a bounding estimate of the reduction in drainage that could be expected when deep-rooted plants are present.

300 AREA FIELD SITE

In January 1983 a network of 25 neutron access wells were placed in a cheatgrass covered site, west of the 300 Area (Kirkham and Gee 1984; Gee and Kirkham 1984). The site is located about 2 km south of the 300 Area lysimeter site. Figure 9 shows the instrumentation and the test well locations at this site. Since early 1983, the moisture profiles at the grass site have been monitored on a biweekly basis. The data indicate that significant quantities of water have moved below the root-zone at this site. Estimates of drainage were made by measuring water content changes below the 1-m depth with time (Figure 10). Errors in storage changes over this depth were estimated to be ±0.5 cm. For an 18-month period of time (January 1983 to June 1984), more than

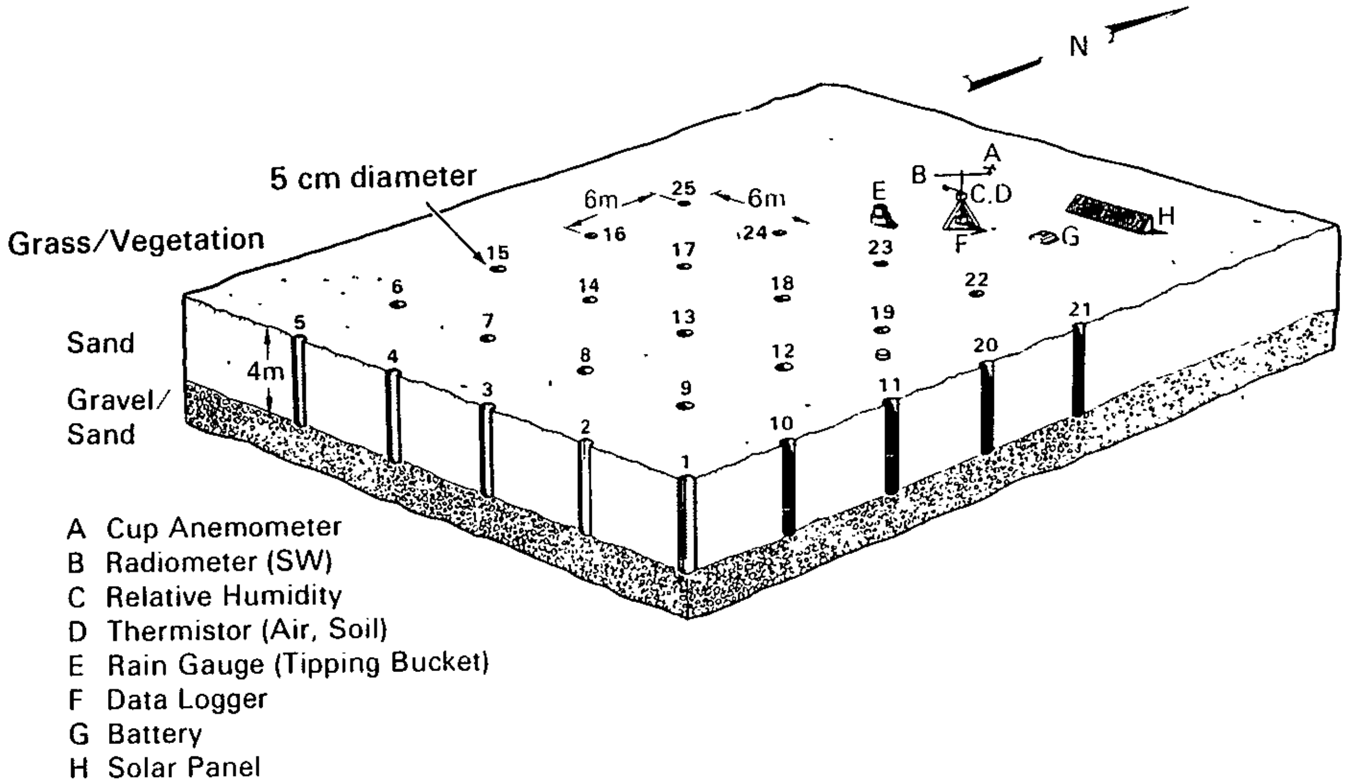


FIGURE 9. Field Site in 300 Area for Monitoring Water Content Changes Below the Root-Zone of Cheatgrass

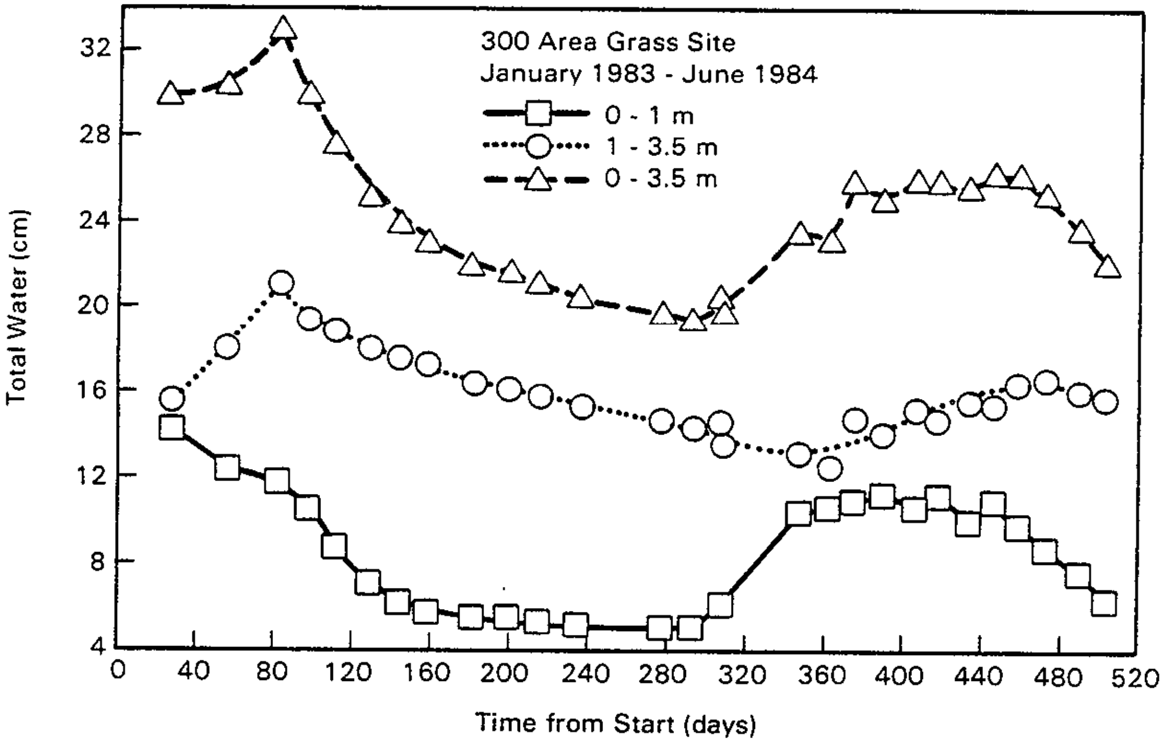


FIGURE 10. Averaged Water Content Changes for Three Depth Increments at the 300 Area Grass Site

10 cm of water moved below the root zone at this site. Monitoring by neutron probe logging has been continued in an attempt to further document the water storage changes at this site.

INJECTION TEST

A recent study by Sisson and Lu (1984) provides some insight into the effects of layering on water movement in the unsaturated zone at Hanford. An injection well and a series of concentric monitoring wells were constructed to monitor the advance of a three-dimensional wetting front in unsaturated sediments. Tracers (Cs-134 and Sr-85) were added to the water to additionally observe radionuclide migration. The purpose of the test was to evaluate numerical computer codes for modeling multidimensional water flow. Because water applications were made by injection at a point at depth, the test more accurately simulated the features of a tank leak rather than recharge by precipitation.

An extensive data set of moisture and radionuclide profiles were developed using downwell logging with neutron moisture probes and gamma counting equipment. The moisture data were tested against model simulations, particularly for positions close to the injection well. The data appeared to agree reasonably well between model simulations and measured moisture profiles for the close well. The agreement between model and measurements was not particularly good at distances beyond about 2 m from the injection well. The discrepancies were attributed to the heterogeneities in the layered sediments and the inability of the model to adequately describe these heterogeneities. No attempt was made to model the radionuclide migration.

In addition to the model simulation comparisons, the report also provides some information on initial and drained moisture contents in subsurface sediments. The initial moisture contents of the layered sediments were not determined by direct gravimetric sampling, but neutron-probe-inferred moisture contents varied from less than 4 to more than 15 vol%. After injection and subsequent drainage, the water content in most cases returned to the initial water contents. These data suggest that the moisture content at depth at this location is not affected by deep evaporation and/or plant roots. It would be instructive to continue to log these monitoring wells to determine the amount of continued redistribution of the injection water over time. Careful analysis of these data may provide in situ hydraulic conductivity values for these unsaturated sediments. Measured hydraulic conductivities can be important for predicting natural recharge. It would be of great interest to evaluate these data further and to quantify the rate of drainage that continues to persist at this site. Also, the effect of sediment layering on both upward and downward migration of water in the unsaturated zone should be further quantified.

TRITIUM STUDIES

Tritium concentrations in precipitation water increased significantly after 1952 as a result of testing of nuclear devices (Stewart and Farnsworth

1968). The elevation in tritium levels in precipitation water was more than an order of magnitude higher than background (pre-1952) levels, suggesting that tritium could be used as a natural tracer for measuring infiltration depths in unsaturated soils (Allison and Hughes 1974).

At the Hanford site, measurements of the depth of penetration of infiltrating water from rainfall/snow melt were determined by measurements of rainout-bomb tritium concentrations in samples taken from drilling cores from well 12-B southeast of the 200 Area (Brownell et al. 1971; Isaacson, Brownell and Hansen 1974). Tritium concentrations measured in 1969 were significantly above background, ranging from more than 1000 tritium units (T.U.)[a] at the surface down to 10 T.U. at 5 m (17 ft) below the soil surface. The initial interpretation of these data was that the 5-m depth correspondeds to the depth of maximum penetration of rainfall/snow melt (meteoric) water. Another interpretation was that during the time interval of nearly 20 years, tritium moved at a relatively constant rate to a depth of 5 m. If the average moisture content of the subsurface sediments was 5% by volume, then the infiltration can be shown to be approximately 2.0 cm/yr (see Heller, Gee and Myers 1985, Appendix D). Measurements of tritium at depth in the soil would be helpful in further identifying the current recharge rate. For example, if recharge has been steady at 2 cm/yr during the past 15 years, then it can be shown that the elevated tritium profile should penetrate to depths of more than 9 m. It seems possible that new studies using tritium could prove valuable in further quantifying the recharge rate at several locations at the Hanford site. The major difficulty would be resolving the tritium concentrations because the rainout-bomb tritium has now decayed through an additional two half-lives since the 1969 tests. However, concentrations in excess of 100 T.U. still should be detectable above background. Studies similar to those conducted by Allison and Hughes (1974) seem appropriate for estimating recharge at this arid site.

(a) T.U. = 3.2 pCi/L.

UNSATURATED FLOW MODEL SIMULATION AND VALIDATION

Over the past 20 years a number of reports have been issued documenting unsaturated water flow modeling efforts for the Hanford site. Efforts initially centered around development of codes that would numerically handle the severe nonlinearities that occur in unsaturated water flow problems, particularly when water moves into dry soil (Reisenauer 1963; Reisenauer et al. 1975; Baca, King and Norton 1978; Baca, Lantz and Fortems 1979; Finlayson, Nelson and Baca 1978). Problems of interest have centered around subsurface flows (e.g., tank leaks) as well as the influence of multiphase (vapor and liquid) flow on the water movement under natural recharge conditions. During the past several years, more attention has been directed toward validation of these unsaturated flow models, particularly with respect to the processes of evaporation, transpiration, redistribution, and drainage in both uniform and layered soils/sediments (Jones, Campbell and Gee 1984; Gee and Kirkham 1984; Sisson and Lu 1984).

The continued development of unsaturated flow codes by the petroleum industry, university research teams, federal agencies, and others (Oster 1982) has improved our overall capability to model flow in the unsaturated zone. The most refined codes handle water flow in a deterministic (i.e., mechanistic) way (Gupta et al. 1978; Simmons and Gee 1981). That is, they assume that unique processes such as infiltration, redistribution, drainage, evaporation, and transpiration can be described mathematically and that these processes are linked and interact together in ways that can be described by well-developed hydrologic laws and equations. The transient nature of water flow (daily and seasonal) in the unsaturated zone, particularly near the soil surface, requires careful control of time steps, grid spacings, and mass balance errors to obtain flow predictions that are reasonable and accurate.

Both single and multidimensional models have been used to study unsaturated flow at Hanford. However, with the exception of tank leak studies (Reisenauer et al. 1975; Sisson and Lu 1984), multidimensional (two-dimensional and three-dimensional) codes have been used sparingly. The complexities and time involved in both running these models and interpreting the results have not justified additional effort. In addition, with the exception of the report by Sisson and Lu (1984), few data are available to adequately test a two- or three-dimensional model.

At this time, no modeling study for the Hanford site has been sufficiently complete so that a particular model can be considered validated. Among the numerous difficulties that we have found in our model validation efforts, the following seem to be the most common.

1. Lack of appropriate data for validation. For unsaturated flow modeling, data from the 200 Area and 300 Area lysimeters are the most extensive. However, no data are available for plant growth and evapotranspiration on the 200 Area lysimeters and only limited amounts of these data are available from the 300 Area lysimeter and grass site.

2. Processes not well enough understood. As an example, evapotranspiration (ET) under arid site climates is poorly understood. Plant communities and their hydrological response are very closely tied to climate variables. Plants can integrate climate changes and adapt to them, but their response to such things as drought or excess water at present is poorly understood.

3. Spatial variability. Precipitation input variations as well as areal distribution of hydrologic properties make it difficult to quantify water flow over large areas. The model validation efforts currently are confined to testing for flow under relatively well-controlled (nearly homogeneous soil) conditions (laboratory columns, field lysimeters, isolated wells, etc.). The model validation efforts with the exception of Sission and Lu's (1984) work have been tested against one-dimensional data sets. Actual field situations particularly in consideration of water balance (evapotranspiraton redistribution and drainage) will require a more detailed evaluation of the heterogeneities of the system, including precipitation (rainfall distribution) soil spatial variability and plant temporal and spatial variability.

Recommendations for continued research in this area include documentation of one- and two-dimensional codes that best describe the unsaturated water flow processes at Hanford. Data bases need to be improved so that the adequacy of the model(s) can be tested over a range of conditions useful in making both immediate decisions regarding waste management options and long-term predictions for performance assessment considerations.

RECOMMENDATIONS

Although flow studies and modeling efforts for the Hanford site have been carried out to varying degrees during the past 20 years, several issues remain to be resolved before a definitive statement can be made regarding the natural recharge rate(s) that result from water transport through the unsaturated zone. Important issues and recommendations for research on these issues are discussed briefly in this section.

1. Unsaturated Hydraulic Conductivity Determinations. In situ measurements of hydraulic conductivity needed to assess drainage and recharge are not currently available except for a few selected tests (Gee and Kirkham 1984; Sisson and Lu 1984). Data are needed that can be used to estimate hydraulic conductivity at typical field water contents for specific sites. Sites where in situ measurements are taken should represent a range of conditions present at the Hanford site (e.g., tank farms, fine and coarse soils, vegetated and non-vegetated surfaces, etc.). Estimates from laboratory samples may provide some insight in the expected range of data, but errors of at least one to three orders of magnitude are not uncommon in the estimation of field hydraulic conductivities from laboratory measurements (Hillel 1982). Continued monitoring of the deep-well injection test may provide some insight into expected field hydraulic conductivities of drained, layered profiles. We recommend that additional data be collected from this site on a quarterly basis over the next 2 to 3 years.

2. Evapotranspiration Measurements. The measurement of evapotranspiration (ET) is critical to an understanding of the water balance at the Hanford site. Direct measurements of ET have not been reported, to date, except for some limited measurements of cheatgrass with a weighing lysimeter (Gee and Kirkham 1984). Additional ET measurements are needed to evaluate independently this component of the water balance. We suggest that over the next 2 to 3 years, additional measurements be made on cheatgrass and also that ET from

deeper rooted plants be measured using weighing lysimetry. A range of annual ET measurements for grasses and shrubs should be made. The appropriate rooting depths, phenology, and other biological controls regulating seasonal and annual water losses by a given plant community should be measured to improve water balance modeling capabilities and long-term predictions of ET. In addition, some effort should be expended to test other methods of ET measurement, including Bowen ratio, eddy correlation (Campbell 1977) and LIDAR (Light Detection And Ranging) techniques (Measures 1984) to obtain areal sampling of ET for selected time periods over typical plant/soil communities at Hanford.

3. Measurement of Tritium Migration. The depth penetration of the rain-out (weapons testing) tritium since 1969 offers some distinct opportunities to evaluate recharge. An effort should be expended to scope the range of tritium contents in core samples at depth for several representative sites. Improved tritium measurement techniques (Jones and Gee 1984) and careful sampling to prevent cross-contamination of samples with depth will enhance the likelihood for success of these tests.

4. Spatial Variability of Natural Recharge. Areas need to be selected in the 200 and 300 Areas and other locations on the site to evaluate the effects of spatial variability on recharge rates. Recharge cannot be predicted from one set of measurements at one site. We suggest that disturbed areas, typical of the waste burial sites, be selected, with and without vegetation. Tests need to be conducted that show the extremes in expected recharge. These sites could be those selected for tritium studies as well--if the location has not been contaminated with tritium from liquid discharges.

5. Effects of Layering on Annual Recharge Rates. The proposed tritium studies and the continued injection well test site monitoring can provide additional information on the effects of soil layering on the recharge rates. This is an important aspect of unsaturated flow at Hanford and is related to the spatial variability issue discussed

previously. An analysis of flow in layered systems under natural conditions will also help evaluate the potential cover systems that incorporate distinct textural differences into their design.

6. Model Validation Efforts. Long-term predictions of recharge rates are necessary for adequate site assessment and for evaluating waste management decisions. Effects of climate change and other plant and soil cover changes need to be simulated to evaluate the changes in recharge rates that might be expected under more severe (e.g., wetter climate, less plant cover, coarser soils) site conditions. Model calibration efforts using currently available data will help in evaluating the performance of unsaturated water flow models in predicting recharge rates and provide some confidence in long-term predictions.

CONCLUSIONS

Unsaturated water flow studies conducted at Hanford during the past 20 years have shown the following:

1. Water contents at depth in Hanford sediments are generally low, ranging from 2 to 7 wt% in coarse- and medium-textured sands and 7 to 15 wt% in silts. The low water contents tend to dominate the profile, but the soils are extremely heterogeneous; hence, soil water content is not a predictable parameter. A combination of coarse texture, low precipitation, and a deep water table gives rise to the observed soil water contents. Measurements of water content alone cannot be used to predict amounts of recharge.

2. Measurements of matric potential in deep sediments (below 10 m) suggest that the water in these sediments is slowly draining to the water table. The rate of drainage depends primarily on the unsaturated hydraulic conductivity of the sediments. Hydraulic conductivity throughout an entire soil profile has not been directly measured to date, but continued monitoring of injection well tests may provide in situ measurements useful for estimating unsaturated hydraulic conductivity.

3. Lysimeter studies in the 200 Area from 1971 through 1977 indicated that, within the precision of the neutron probe measurements (±1% vol), the resolution of recharge rate was about ±2.6 cm/yr. The trend in the probe readings, however, suggest that water did not move below the 4-m depth over the 6-year test period. Water removal by plant extraction is a possible explanation for the low rate of recharge at this location.

4. Lysimeter and field studies in the 300 Area from 1979 through 1984 indicated that water is moving at depths below the plant root-zone. Recharge rates from bare soil exceeded 5 cm/yr for the past 2 years. Estimates of recharge from the grass-covered field sites ranged from

3 to 8 cm/yr. Coarse-textured soils, shallow-rooted plants, combined with above-normal precipitation, have optimized conditions for recharge at this location.

5. Tritium sampling of unsaturated sediments indicated that infiltrating water at a 200 Area site moved to depths of 5 m by 1969. If steady recharge is occurring, tritium levels at this test site should have increased with depth since 1969. For example, a steady flux of 2 cm/yr would cause present-day levels of tritium in soil water to be elevated above background levels down to depths of 9 m or more. Further testing of water migration using tritium tracers is warranted.

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

CHARACTERIZATION OF THE UNSATURATED ZONE

A number of important parameters are needed to characterize the hydrology of the unsaturated zone. They include soil water content, soil water potential, saturated and unsaturated hydraulic conductivity, and water retention characteristics of the soils and sediments within the unsaturated zone. These parameters, along with climatic data and plant transpiration functions, are those needed to quantify the water balance at a specific site. The parameters are described in detail in soil physics and hydrology texts (e.g., Hillel 1982; Freeze and Cherry 1979). Other analyses that help quantify the water storage and transport properties for unsaturated soils include textural analysis, analysis of vapor transport characteristics and thermal properties, and the analysis of spatial distributions of hydraulic properties. While not all of the above information may be required to adequately characterize the unsaturated zone at a given site, the level of detailed information needed depends on the type of hydrologic analysis that is to be performed. A simple assessment of the potential for drainage at a given site may requre no more than an estimate of preciptation and evaporation and a textural analysis to estimate the infiltration capacity of the soil. A more detailed assessment, which attempts to quantify the amount of recharge at a given site, may require a deterministic model that incorporates detailed climatic inputs, such as diurnal and seasonal distributions of rainfall, radiation and humidity, and in addition includes all known hydraulic and thermal properties of the soil. Such a model may be needed when evaporation rates are not well known, to account for vapor as well as liquid water flow mechanisms.

Table A.1 lists the unsaturated zone characteristics identified in published reports for the Hanford site. Some of these reports were prepared primarily as basic characterization reports while others have attempted to synthesize the data into an analysis of water infiltration and quantify the

TABLE A.1. Unsaturated Zone Characteristics Identified in Published Reports for the Hanford Site

Characteristics	References (See Appendix 1)
Water Content	
Gravimetric	9,10,11
Neutron probe	1,2,10,11,12,13,14,15,16,17,18
Water Potential	
Psychrometer	1,2,4,15
Block	15,20
Tensiometer	3,15
Pressure plate	3,9,22,23
Hydraulic Conductivity	
Saturated	3,6,7
Unsaturated	7
Water Retention	
Desorption curves	3,5,6,7,9
Sorption curves	7
Water Balance	
Storage changes	1,2,8,11,13,14,15,16,17,18
Evaporation-measured	8,17
Evaporation-computed	5,8
Drainage-measured	8,17
Drainage-computed	1,4,8,9,15,17,21
Spatial Variability	
Water content	9,22
Hydraulic conductivity	9

TABLE A.1. (contd)

Characteristics	References (See Appendix 1)
Temperature	
Thermal conductivity	3,5
Thermal profiles	1,2,5,13,18
Texture	
Particle size analysis	19,22
Model Simulations	
Unsaturated water flow	5,8,16,17,21,23
Storage changes	5,8,16,17
Evapotranspiration	8,17

amount of recharge that may be occurring at selected sites at Hanford. To date, there has been no comprehensive study of the unsaturated zone at Hanford that delineates zones of potential recharge and demonstrates the use of a validated model that could be used to accurately predict recharge rates at Hanford. The following section of this report highlights, by annotation, the important information that is currently available on the unsaturated zone at Hanford. The synthesis of this information into a comprehesive analysis, which can adequately deal with the recharge question, is part of a planned research effort scheduled for completion in FY 1988.

APPENDIX 1

ANNOTATED REFERENCES ON THE UNSATURATED ZONE AT HANFORD

1. Brownell, L. E., J. G. Backer, R. E. Isaacson, D. J. Brown. 1975. Soil Moisture Transport in Arid Site Vadose Zones. ARH-ST-123, Atlantic Richfield Hanford Company, Richland, Washington.

ABSTRACT

Measurements for the Lysimeter Experiment and the Thermocouple Psychrometer Experiment have continued with a new series (of measurements) using closely spaced sensors installed to a depth of 1.52 meters. During the 1973-1974 water year the percolation envelope of higher moisture content penetrated to a depth of 4 meters in the closed-bottom lysimeter and then was eliminated by upward transport of water in late summer. Precipitation during the 1973-1974 water year percolated to a depth of about six meters in the open-bottom lysimeter and remains as a residual perched envelope. The increase over normal percolation was due in part to a residual envelope of higher moisture content from the previous water year. Data to be collected during the 1974-1975 water year should provide information on whether or not the envelope will continue its downward movement or reverse direction and move upward. The equilibration of the thermocouple psychrometers with the surrounding soil now allows for more accurate measurements of water potential. Future work will develop relationships between matric potential, depth of percolation, soil characteristics, and seasonal climatic variations.

Annotation: Discusses the use of two deep (18 m) lysimeters (1 open, 1 closed bottom) and one uncased well in studying soil moisture transport through Hanford sediments. Presents moisture data obtained using thermocouple psychrometers and a neutron probe. Suggests that soil moisture profiles, which have stayed relatively stable for several years (since 1971), indicate that little water, if any, is moving at depths below 6 m.

3. Cass, A., G. S. Campbell and T. L. Jones. 1981. Hydraulic and Thermal Properties of Soil Samples from the Buried Waste Test Facility. PNL-4015, Pacific Northwest Laboratory, Richland, Washington.

SUMMARY

The Department of Energy's (DOE) Low-Level Waste Management Program is providing the technology necessary to properly dispose of low-level radioactive waste. As part of this effort, Pacific Northwest Laboratory (PNL) is studying soil water movement in arid regions, as it applies to shallow land burial technology.

Shallow land burial, the most common disposal method for low-level waste, places waste containers in shallow trenches and covers them with natural sediment material. To design such a facility requires an in-depth understanding of the infiltration and evaporation processes taking place at the soil surface and the effect these processes have on the amount of water cycling through a burial zone. At the DOE Hanford Site in Richland, Washington, a field installation called the Buried Waste Test Facility (BWTF) has been constructed to study unsaturated soil water and contaminant transport. PNL is collecting data at the BWTF to help explain soil water movement at shallow depths, and specifically evaporation from bare soils. The data presented here represent the initial phase of a cooperative effort between PNL and Washington State University to use data collected at the BWTF to study the evaporation process and how it relates to the design of shallow land burial grounds.

The method of characterizing evaporation from bare soils, being evaluated in the current study with Washington State University (WSU), involves calculating, what is called, the coupled flow of mass and energy. In most flow calculations, this "coupling" is ignored; however, evaporation is one process where such a simplification may not be justified. The WSU effort is, therefore, designed to consider coupling when evaluating evaporation from bare soils. The goal of this initial phase has been to use samples of soil from the BWTF to measure transport coefficients and soil properties that are fundamental to the analysis of evaporation.

This report briefly discusses the theory of heat and water flow to illustrate the importance of the coefficients and properties measured. Materials and methods used in the laboratory analyses are described and referenced. The transport coefficients that were measured are those needed to describe the uncoupled or independent flow of heat and water. Future work will include calculation of the additional coefficients needed to describe the coupling and interaction of heat and water flow, and the application of this analysis to describing evaporation at the BWTF. The properties and coefficients measured include soil characteristic function, hydraulic conductivity, thermal conductivity, bulk density, and particle size distribution.

Annotation: Discusses the setup of the BWTF. Includes a short discussion on the theory of heat and water flow in soil and relates it to the measured coefficients and properties of soil from the BWTF. Properties presented include water retention characteristics, texture, density, and thermal conductivity.

2. Brownell, L. E., R. E. Isaacson, J. P. Sloughter, M. D. Veatch. 1971. Moisture Movement in Soils on the Hanford Reservation. ARH-2068, Atlantic Richfield Hanford Company, Richland, Washington.

INTRODUCTION

All methods considered feasible for long-term storage of radioactive wastes are based on the concept of preventing radioactive material from dispersal in natural water supplies, viz., surface water, groundwater, and oceans. This is fundamental because if such dispersal should occur at any point, the process is in practice irreversible and it is, for practical purposes, impossible to regain control of the radioactive substances dissolved or suspended in the water. Because of the basic criterion of maintaining a separation between radioactive wastes and natural water supplies, Erichsen proposes that radioactive materials be stored in arid areas.

The possible migration of radionuclides stored in the soils of the vadose zone is of primary importance at the Hanford Reservation. Liquid waste of low and intermediate levels (<5 x 10^{-5} μCi/ml and 5 x 10^{-5} -100 μCi/ml) have been allocated to swamps, cribs, dry wells, and trenches. For immobilization, all of these procedures rely on the absorption of radionuclides within a few feet of the soil surface, and/or the lack of liquid percolation to the water table to prevent dispersion to natural water supplies.

The following program is proposed to study the phenomena of soil moisture movement at the Hanford Reservation and to determine locally if there is a net transfer of water from the water table to the surface, as postulated, rather than from the surface to water table. The program is necessary to define more completely the potential hazards and problems of radionuclides stored in the subsoil, and to examine the possibility of long-term storage of selected nuclear waste at the Hanford Reservation.

Annotation: Presents equations that relate the soil saturation to the water potential using various soil characteristics to determine if water will percolate through the soil profile to the water table. Discusses initial results of the Deep Well Test and related studies to evaluate matric potential in Hanford sediments.

4. Enfield, J. J. C. Hsieh, and A. W. Warrick. 1973. Evaluation of Water Flux Above a Deep Water Table Using Thermocouple Psychrometers, Soil Sci. Soc. Amer. Proc., vol. 37, pp. 968-970.

ABSTRACT

Deep water flow was evaluated in a Washington desert environment using hydraulic conductivity and potential gradients. Thermocouple psychrometers and temperature transducers were installed to depths of 94 m in the soil profile and used to measure the potential gradients. The hydraulic conductivity was calculated using a modified Millington and Quirk equation and the soil moisture characteristic curve. The thermal fluid diffusivity was calculated and used to estimate flow induced by thermal gradients. Under the conditions studied, a more refined analysis of the thermally induced flow is required to give a definite answer as to the direction of flow. It was concluded, however, if flow existed at this location, it was less than 1 cm/year.

Annotation: Discusses results of measurements from thermocouple psychrometer for matric potential and diode transducers for temperature in an uncased well in the deep unsaturated zone (94 m thick) at Hanford over several months period during 1970. Flow calculations were based on a coupled heat and water flow analysis. Thermal gradients at depths below 10 meters suggest that thermally induced vapor could produce steady upward flow of about 0.004 cm/yr while liquid hydraulic conductivity estimates suggest downward flow of about 0.03 cm/yr. Variability in moisture release curve and hydraulic conductivity data make exact determination of rate or even direction of flow uncertain.

5. Finlayson, B. A., R. W. Nelson, and R. G. Baca. 1978. A Preliminary Investigation into the Theory and Techniques of Modeling the Natural Moisture Movement in Unsaturated Sediments. RHO-LD-47, Rockwell Hanford Operation, Richland, Washington.

ABSTRACT

A study was performed on the problem of developing a general computer model of fluid flow processes in arid site soil systems. This report presents the results of work in three specific areas: 1) formulation of a detailed mathematical model, 2) numerical solution of the governing nonlinear partial differential equations, and 3) application of a one-dimensional computer model to a field situation. Major focus of the study was the investigation of traditional numerical techniques for solving the strongly nonlinear equations of unsaturated flow theory.

A generalized mathematical model is formulated which considers the fluid flow processes of capillary, gravity, thermally induced liquid and vapor transport, and heat conduction. The concepts advanced by Philips and de Vries are used in describing the temperature effects of fluid transport. Three fluid phases are considered in the unsaturated flow model, namely: liquid, vapor, and air. The generalized model is expressed as five nonlinear partial differential equations.

Numerical methods such as finite difference, collocation, and finite element techniques are reviewed and evaluated. Based on the numerical experiments of this study, a finite difference method with upstream weighting is found to be a recommended approach. This approach, however, possesses limitations related to the degree of nonlinearity. The degree of difficulty associated with solving the nonlinear partial differential equations is related to the properties of matrix stiffness. A coefficient ratio is developed to provide a measure of matrix stiffness which can be computed directly from the soil-water hydraulic properties.

A preliminary computer model based on a simplified model formulation is applied using data for a field lysimeter. Comparisons between measured and computed moisture profiles are made for the lysimeter. Only qualitative agreement was obtained in these tests. In addition, the numerical solution technique was found to be stable for only certain cases. Further testing would be needed to fully check out this preliminary model.

Additional research is needed to develop numerical solution techniques which are accurate, stable, and computationally efficient. The finite element techniques used in conjunction with a rapidly convergent iterative algorithm is a promising approach. Simpler mathematical formulations should be used in developing practical predictive models for natural moisture transport.

Annotation: Discusses problems in developing a computer model of fluid (liquid and vapor) flow processes in arid site soil systems. Significant detail given on model assumptions and numerical techniques required to solve a highly complex, nonlinear flow problem. Little detail given on how the computer simulations were generated to compare model calculations with field data. Generally poor agreement was obtained between observed and calculated moisture profiles.

6. Gee, G. W. and A. C. Campbell. 1980. Monitoring and Physical Characterization of Unsaturated Zone Transport. Laboratory Analysis. PNL-3304, Pacific Northwest Laboratory, Richland, Washington.

SUMMARY

Unsaturated column studies on Hanford sediments indicated that:

1. The sorption of relatively mobile nuclides such as tritium, cobalt-EDTA, and technetium could be measured with greater precision using the unsaturated column tests than with batch methods. Although general agreement was obtained between the two methods, the adsorption coefficient (Kd) values for tritium, cobalt-EDTA, technetium and iodine were less variable and better defined with the unsaturated column tests than with batch tests. Kd values for strontium from unsaturated column tests agreed well with batch test determinations.

2. Little or no difference in sorption was observed when the flow rates were changed by more than an order of magnitude (2 to 50 cm/day).

3. Changes in saturation percentage of the soil, from 56 to 31%, also had only a minor effect on nuclide sorption.

4. For layered sediments, the effective sorption of a layered sequence is controlled by the sorption characteristics of the most sorbing layer.

Annotation: Discusses sorption of radionuclides by geologic material from a sandy soil typical of many surface materials on the Hanford site. Measured unsaturated hydraulic conductivities for this sandy soil ranged from 2.2 cm/day to 49 cm/day as water content varied from near 31 vol% to 56% (saturation).

7. Gee, G. W., A. C. Campbell, P. J. Wierenga, and T. L. Jones. 1981. Unsaturated Moisture and Radionuclide Transport. PNL-3616, Pacific Northwest Laboratory, Richland, Washington.

SUMMARY

This report describes several laboratory procedures and computer model simulations used to evaluate the transport of water and radionuclides through unsaturated Hanford soils.

The unsaturated hydraulic conductivity was measured using the steady state methods of Klute (1972) and the transient state method of Rose (1968). These experimental data were compared to the conductivity models of Millington and Quirk (1961); Davidson et al. (1969); Campbell (1974); van Genuchten (1980a); and Bresler, Russo and Miller (1978). Good agreement was found between all methods in the wet range; however, disagreement was found in the dry range. The method of Davidson et al. (1969) overpredicted the conductivity by several orders of magnitude in the <10% volumetric moisture content range. The other methods underpredicted the conductivities in this range. The power function approach of Campbell (1974), and Bresler, Russo and Miller (1978) best predicted the measured conductivities. However, none of the conductivity models explicitly addresses the water vapor component of the conductivity. This may explain the underprediction of the hydraulic conductivity in the dry range where vapor transport is important.

Radionuclide transport through unsaturated media was investigated by using two solute transport models to describe the transport of tritium and strontium-85 in laboratory columns. A two parameter convective-dispersive model was compared with a four parameter mobile-immobile water model (van Genuchten and Wierenga 1976a). Both models adequately described the movement of tritium and strontium through small (5 cm x 27.5 cm) columns and the movement of tritium through a large (0.5 m x 1.7 m) column.

The dispersion coefficient was found to be sensitive to changes in both velocity and column length. The mobile-immobile water equations were not as sensitive to changes in experimental scales at the convective-dispersive equation.

Both models were relatively successful in describing the rapid flush of strontium-85 from a column initially leached with a low salt solution followed by a high salt solution, a phenomena called the snow plow effect. The four parameter mobile-immobile water model predicted the initial release of the strontium more accurately than the two parameter convective-dispersive model. Both models confirm enhanced mobility of strontium-85 with leaching solutions of increased salt concentration.

Annotation: Presents problems of choosing a computer model for fluid flow processes in arid site soils. Discusses testing and modeling radionuclide transport in Hanford sediments.

8. Gee, G. W. and R. R. Kirkham. 1984. Arid Site Water Balance: Evapotranspiration Modeling and Measurements. PNL-5177, Pacific Northwest Laboratory, Richland, Washington.

INTRODUCTION

Shallow land burial is the primary disposal method for low-level radioactive waste. Sites in the arid west, where precipitation is low and where thick, unsaturated soil zones persist, are generally considered the most ideal for this type of waste disposal (Mercer, Rao and Marine 1983). These sites provide an environment that tends to minimize contact of water with the waste, thereby minimizing the potential problem of ground-water contamination.

There has been considerable interest in documenting the amount of water flow that actually occurs at depth in the unsaturated zone at arid sites (Brownell et al. 1975; Jones 1978; Winograd 1981). Estimates of water flow rates in the unsaturated zone at the Department of Energy's Hanford site (Washington) and Nevada Test Site have generally ranged from a few millimeters or less, to slightly over 1 cm/yr (Winograd 1981; Jones 1978; Wallace 1978). Detailed water balance studies at these arid sites are needed to better quantify the amounts of water that may be available for the transport of radionuclides.

Recent lysimeter studies (Jones, Campbell and Gee 1983) at the Hanford site indicate that significant quantities of water flow (in excess of 5 cm/yr drainage) can occur in bare soils under arid conditions (16 to 25 cm of annual precipitation). However, most burial sites will likely have some vegetative cover, which can transpire significant quantities of water, thus, reducing the amount available for drainage. This report describes a field study at the Hanford site where the water balance of a grass-covered site has been measured and where efforts have been made to simulate the water balance of the site using an unsaturated flow model, UNSAT-1D.

Annotation: Water storage changes were determined by neutron probe logging of soils in and below the root-zone at a grass covered site in the 300 Area at Hanford. These data indicated drainage was occurring at this site. The data agreed qualitatively with UNSAT-1D model simulation runs and also support similar observations of drainage from the PNL Buried Test Waste Facility located in the 300 Area.

9. Heller, P. R., G. W. Gee, and D. A. Myers. 1985. Moisture and Textural Variations in Unsaturated Soils/Sediments Near the Hanford Wye Barricade. PNL-5377, Pacific Northwest Laboratory, Richland, Washington.

INTRODUCTION

This report documents a recent effort to hydrologically characterize vadose zone sediments at Hanford. The report details measurements of field water contents for samples collected from five boreholes drilled, a few km west of the Wye barricade about 15 km northwest of Richland, Washington. Laboratory analyses were performed on samples from all holes to determine particle size water retention characteristics, hydraulic conductivity, calcium carbonate content, pH, and electrical conductivity. Thermocouple psychrometer data were used to index the matric water potential of field samples from three of five holes. Results are tabulated by hole and depth and a general discussion regarding the use of this information for hydrologic modeling is provided.

Annotation: Presents detailed physical characterization of Hanford site soils. Included are textural analysis, chemistry, field moisture content, and water retention characteristics of soils from the surface down to about 40 m. The data suggest that the soils in this area are draining, but the rate is unknown at present. One of the appendices also discusses travel times through the unsaturated vadose zone.

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10. Hsieh, J. J. C., A. E. Reisenauer, and L. E. Brownell. 1973. A Study of Soil Matric Potential and Temperature in Hanford Soils. BNWL-1712, Battelle, Pacific Northwest Laboratories, Richland, Washington.

SUMMARY

This document describes in detail the construction and installation of a string of thermocouple psychrometers and diode temperature transducers in the soil between the soil surface and the ground water table on the Hanford Reservation. The results of fifteen months of data gathering from these instruments indicate that moisture movement in the soil profile, if any, is extremely small.

Annotation: Presents textural analysis, water content and temperature at various depths (from soil surface to water table at 94 m), for an uncased well located 5 km south of the 200-E Area. Includes profiles of soil temperature and average soil matric potentials at various times of the year (1970-1972).

11. Hsieh, J. J. C., L. E. Brownell, and A. E. Reisenauer. 1973. Lysimeter Experiment, Description and Progress Report on Neutron Measurements. BNWL-1711, Battelle, Pacific Northwest Laboratories, Richland, Washington.

SUMMARY

Two large lysimeters were installed in the soil of the Hanford Reservation to gather data on the accumulation and penetration of meteoric water. This report describes the construction details of this experiment. The soil hydraulic characteristics and data collected for the first 6 months are included.

Annotation: Discusses installation and initial data collection for two deep (18 m) lysimeters located 5 km south of the 200-E Area at Hanford. Information includes desorption curves, hydraulic conductivity, and measured soil water contents.

12. Isaacson, R. E. 1982. Supporting Information for the Scientific Basis for Establishing Dry Well Monitoring Frequencies. RHO-RE-EV-4-P, Rockwell Hanford Operations, Richland, Washington.

ABSTRACT

A scientific basis has been developed for establishing the frequency of monitoring dry wells. Dry wells are used to detect radioactivity from a leaking underground high-level radioactive waste storage tank. The frequency of monitoring a dry well is dependent on the response characteristics of the radiation-detection system used periodically to monitor dry wells for encroaching radioactivity. The response characteristics of the detection system have been combined in the Dry Well Radioactivity Response Equation.

The Dry Well Radioactivity Response Equation is derived using the following information:

- Variation in dose rate (roentgen per hour) as a function of source strength
- Variations in dose attenuation by the soil as the radioactive waste front approaches the dry well
- Response of radiation detector, in counts per second, as dose rate changes (instrument calibration)
- Distance of dry well from tank leak source
- Leak rate
- Geometry of soil wetted by leaking waste
- Hydrologic properties of the soil.

These variables are used with the current status of tank contents and available liquid-level monitoring system information to generate a monitoring schedule for individual dry wells and horizontal laterals associated with single-shell, high-level waste storage tanks on the Hanford Site.

Annotation: Detailed graphs, tables, pictures, and locations of the waste tanks at the 200 (East and West) Areas. Neutron probe determined moisture contents for soils in the tank farms areas are listed in Table E-2.

13. Isaacson, R. E., L. E. Brownell, and J. C. Hanson. 1974. Soil Moisture Transport in Arid Site Vadose Zones. ARH-2983, Atlantic Richfield Hanford Company, Richland, Washington.

<u>ABSTRACT</u>

Soil moisture transport processes in the arid soils of the Hanford site are being evaluated. The depth of penetration of meteoric precipitation has been determined by profiling fall-out tritium at two locations where the water table is about 90 meters below ground surface. In situ temperatures and water potentials were measured with temperature transducers and thermocouple psychrometers at one of these locations to obtain thermodynamic data for identifying the factors influencing soil-moisture transport. Neutron probes are being used to monitor soil moisture changes in two lysimeters, three meters in diameter by 20 meters deep. The lysimeters are also equipped to measure pressure, temperature, and water potential as a function of depth and time. Nonisothermal soil moisture transport processes are being studied. A thermal pump that moves water towards the surface exists as a result of annual sinusoidal oscillation of temperature in the upper nine meters of soil. A partially desiccated zone exists at a depth between 9 to 16 meters. Future work will be concerned with further study of these systems and the coupling of theoretical and experimental work and determining the amount of rainfall required to cause migration of soil moisture to the water table.

<u>Annotation</u>: Discusses tritium movement, as well as water potential and temperatures gradients present in soil profiles at Hanford site. Includes information on geothermal gradient and seasonal temperature cycles at Deep Well Test from February 1971 to April 1972.

14. Jones, T. L. 1978. Sediment Moisture Relations: Lysimeter Project 1967-1977 Water Year. RHO-ST-15, Rockwell International, Rockwell Hanford Operations, Richland, Washington.

INTRODUCTION

Throughout the history of the Hanford Project, low-level radioactive wastes have been released into the unsaturated Hanford sediments through several disposal methods. These methods have used the sorptive capacities as well as the arid nature of these sediments to isolate the waste material within this unsaturated zone. Moisture movement within the unsaturated sediments may be capable of transporting these waste materials away from their initial storage site. For this reason, research to characterize moisture movement above the water table was initiated as part of the long-term management of low-level waste project.

Two large field lysimeters were constructed in 1971 to evaluate the possible vertical movement of naturally occurring sediment moisture. These lysimeters are located approximately one mile south of the 200 East Area. This report presents and evaluates sediment moisture data collected at the lysimeter site from September 1976 through August 1977, which is the 1976-77 water year.

Annotation: Discusses ongoing data collection from the two 18 m deep lysimeters located just south of 200-E Area at Hanford. Discusses some of the limitations of using neutron probes in resolving moisture content differences and concludes that soil hydraulic conductivity is an important parameter needed to calculate expected recharge at the lysimeter site.

15. Jones, T. L. and G. W. Gee. 1984. Assessment of Unsaturated Zone Transport for Shallow Land Burial of Radioactive Waste. PNL-4747, Pacific Northwest Laboratory, Richland, Washington.

<u>SUMMARY</u>

This report documents research activities conducted by Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy's National Low-Level Waste Management Program. The research relates to radionuclide transport at an arid shallow-land burial site. A general discussion on the technology needs at arid-zone sites emphasizes the unique features of an arid site for radioactive waste disposal. These features include low precipitation, deep water tables and generally remote site conditions. We discuss the interaction between climate, soil, plants, engineered barriers and the buried waste in terms of the performance of a waste disposal system at an arid site. Justification is given for detailed unsaturated flow and transport modeling for long-term assessment of shallow land burial (SLB) sites. An approach to this modeling effort is outlined.

Two main topics are addressed in this report. The first topic relates to the assessment process for shallow land burial site design. This overview includes basic descriptions of water balance, transport processes and technology needs for waste management at an arid (dry) site. The second topic deals with specific results of research activities at PNL related to water and radionuclide transport under arid, shallow land burial conditions.

The monitoring technology, water balance, and radionuclide transport at arid sites are discussed, and the use of neutron probes, electrical resistance units, tensiometers, and psychrometers are explained and examples given on their applications in arid-site monitoring. Measurements of water flow and radionuclide transport coefficients needed to describe movement in unsaturated soils are documented.

<u>Annotation:</u> Discusses needs and goals of shallow land burial technology in general. Includes discussion on computer model verification studies and summarizes five years of PNL research efforts in unsaturated water flow in the 300 Area at Hanford. Field data on measured drainage from the 300 Area burial ground lysimeters is presented along with profiles of tritium and cobalt-EDTA under irrigated and non-irrigated conditions.

16. Jones, T. L., G. S. Campbell, and G. W. Gee. 1984. Water Balance at an Arid Site: A Model Validation Study of Bare Soil Evaporation. PNL-4896, Pacific Northwest Laboratory, Richland, Washington.

SUMMARY

This report contains results of model validation studies conducted by Pacific Northwest Laboratory (PNL) for the Department of Energy's (DOE) National Low Level Waste Management Program (NLLWMP). The model validation tests consisted of using unsaturated water flow models to simulate water balance experiments conducted at the Buried Waste Test Facility (BWTF) located at the Department of Energy's Hanford site, near Richland, Washington. The BWTF is a lysimeter facility designed to collect field data on long-term water balance and radionuclide tracer movement. It has been operated by PNL for the NLLWMP since 1978. An experimental test case, developed from data collected at the BWTF, was used to evaluate predictions from different water flow models.

The major focus of the validation study was to evaluate how the use of different evaporation models affected the accuracy of predictions of evaporation, storage, and drainage made by the whole model. Four evaporation models were tested including two empirical models and two mechanistic models. The empirical models estimate actual evaporation from potential evaporation; the mechanistic models describe water vapor diffusion within the soil profile and between the soil and the atmosphere in terms of fundamental soil properties, and transport processes. The two empirical models were a method documented by Nimah and Hanks (1973), and a method proposed by Beese, van der Ploeg and Richter (1977). The vapor diffusion models used were based on the work of Hammel, Papendick and Campbell (1981). The two vapor diffusion models differed in whether they accounted for water content and temperature gradients (nonisothermal), or just water content gradients (isothermal) to describe vapor flow. In addition to examining the effects of using different evaporation submodels, the sensitivity of model predictions to rainfall distribution, and to the presence or absence of evaporation on rain days was also examined.

Annotation: Discusses theory of computer evaporation models. Uses BWTF data for testing selected computer models which simulated bare soil evaporation. Presents predictions of annual evapotranspiration and drainage at the 300 Area test site.

17. Kirkham, R. R. and G. W. Gee. 1984. Measurement of Unsaturated Flow Below the Root Zone at an Arid Site. PNL-SA-116229, Pacific Northwest Laboratory, Richland, Washington.

ABSTRACT

We measured moisture content changes below the root zone of a grass-covered area at the Hanford Site in Washington State and determined that drainage exceeded 5 cm or 20% of the total precipitation for a 12-month test period (November 1982 through October 1983). Although the average annual rainfall at the Hanford Site is 16 cm, the test year precipitation exceeded 24 cm with nearly 75% of the precipitation occurring during a 6-month interval (November through April). The moisture content at all depths in the soil reached a maximum and the monthly average potential evapotranspiration reached a minimum during this period of time.

Moisture content profiles were measured at depth, with a down-well neutron probe, on biweekly intervals from January through October, and these data were used to estimate drainage from the profile. Grass roots were not found below 1 m, hence moisture changes below 1 m were assumed to be entirely due to drainage. Upward capillary flow was considered to be negligible since the soil was a coarse sand and the water table was below 10 m. The large amount of drainage from this arid site is attributed to rainfall distribution pattern, shallow root-zone, and soil drainage characteristics. These observations confirm earlier observations by Cline et al. (1977) that drainage can occur below grass-covered areas at the Hanford Site.

Unsaturated flow model simulations predicted about 5 cm drainage from the grass site using daily climatic data, estimated soil hydraulic properties, and estimated transpiration parameters for cheatgrass at the Hanford Site. Improvements in the comparisons between measured and predicted drainage are anticipated with field-measured hydraulic properties and more realistic estimates of grass cover transpiration. However, both measurements and model predictions support the conclusion that under conditions where above average rainfall occurs during periods of low potential evaporation and where soils are coarse textured, significant drainage can occur from the root zone of vegetated areas at Hanford or similar arid zone sites.

Annotation: Discusses neutron probe measurements and estimates of drainage of water below the root zone at an arid site. Presents an explanation of the modeling done on the data and measurements of evapotranspiration using weighing lysimeters.

18. Last, G. V., P. G. Easley, and D. J. Brown. 1976. Soil Moisture Transport During the 1974-1975 and 1975-1976 Water Years. ARH-ST-146, Atlantic Richfield Hanford Company, Richland, Washington.

ABSTRACT

The rate and direction of soil moisture movement in Hanford sediments was determined for the 1974-1975 and 1975-1976 water years. The data for these determinations was obtained from two large lysimeters located on the 200 Area plateau near the center of the Hanford Reservation.

During the 1974-75 water year, meteoric moisture percolated to a depth of 2.5 meters with a peak moisture content of 10.5 vol%. This percolation envelope was eliminated by evaporation during the hot dry summer of 1975. The 1975-76 water year had only 70% of the normal precipitation, thus the percolation envelope was small and penetrated to a depth of only two meters. However, in spite of this shallow depth and low volume of moisture, the percolation envelope was not eliminated by the end of the water year because of lower seasonal temperatures and higher humidity during the drying season. Moisture content of sediments in the 4-18 meter depth range showed no relative change throughout the two water years, and no moisture accumulated at the bottom of the lysimeters, which indicates there is no deep percolation of meteoric moisture at this site, and no recharge to the groundwater.

Annotation: Summarizes data from the two 18-m-deep lysimeters for water years 1974-1975 and 1975-1976. Data suggest that the majority of the water movement occurred in the top 4 m during the 2 water years studied. Moisture storage changes below the 4-m depth for this some time period were not detectable using neutron probes.

19. McHenry, J. R. 1957. Properties of Soils of the Hanford Project. HW-53218, Hanford Atomic Products Operation, General Electric Company, Richland, Washington.

INTRODUCTION

A large number of wells have been drilled within the borders of the Hanford project. These wells were constructed for various purposes. In recent years many of the wells were drilled to permit monitoring of the ground water and to investigate the subsurface formations in the vicinity of waste disposal facilities or to provide data for a geologic survey of the region. Soil samples were collected at specified depth intervals from these wells at the time of drilling. The samples are considered representative of the soil horizons through which the well was drilled.

The utility of a given location for the disposal of radioactive waste solutions is dependent upon the moisture retention and cation exchange capacity of the soil profile. An evaluation of the capacity of a given site for liquid radioactive waste disposal is based on the results of a number of laboratory tests. These tests characterize either directly or indirectly, the moisture holding and cation exchange capacities of representative soil samples from the site. Data from these tests, as well as from other laboratory tests, also supplement the geologic study of the project. Portions of these results have appeared in various research and development reports and other portions will appear in forthcoming reports.

This report presents a compilation of the complete results obtained from a number of laboratory tests performed on soil samples selected as representative of various Hanford project well locations.

Annotation: Presents physical characteristics of the various layers of soils from wells located on the Hanford site down to a depth of 200 m (600 ft). Characteristics include textural analysis, pH, 15 bar water contents, and the CEC (cation exchange capacity).

20. Phillips, S. J., A. C. Campbell, G. W. Gee, H. H. Hoober, and K. L. Schwarzmiller. 1979. A Field Test Facility for Monitoring Water/Radionuclide Transport Through Partially Saturated Geologic Media, Design Construction, and Preliminary Description. PNL-3226, Pacific Northwest Laboratory, Richland, Washington.

SUMMARY

Shallow land burial has been a common practice for disposing radioactive waste materials since the beginning of plutonium production operations.

Accurate monitoring of radionuclide transport and factors causing transport within the burial sites is essential to minimizing risks associated with disposal. However, monitoring has not always been adequate. Consequently, the Department of Energy (DOE) has begun a program aimed at better assuring and evaluating containment of radioactive wastes at shallow land burial sites. This program includes a technological base for monitoring transport.

As part of the DOE program, Pacific Northwest Laboratory (PNL) is developing geohydrologic monitoring systems to evaluate burial sites located in arid regions. For this project, a field test facility was designed and constructed to assess monitoring systems for near-surface disposal of radioactive waste and to provide information for evaluating site containment performance. The facility is an integrated network of monitoring devices and data collection instruments. This facility is used to measure water and radionuclide migration under field conditions typical of arid regions. Monitoring systems were developed to allow for measurement of both mass and energy balance.

Annotation: Describes the site characteristics and the building of the BWTF lysimeter facility in the 300 Area.

21. Reisenauer, A. E., D. B. Cearlock, C. A. Bryan, and G. S. Campbell. 1975. Partially Saturated Transient Groundwater Flow Model Theory and Numerical Implementation. BNWL-1713, Battelle, Pacific Northwest Laboratory, Richland, Washington.

SUMMARY

This report describes the mathematical development of a computer model, the Partially-Saturated Transient Flow Model (PST), used to test the formulation for simulating isothermal, unsaturated, liquid flow in heterogeneous porous media. The fundamental equations and assumptions applying to the model are discussed. Problems encountered in modeling the flow in soils with water contents less than saturation are also delineated.

Because of the nonlinearities of the descriptive equations, finite difference approximation and an iterative technique were used to obtain solutions. The model, when tested, was computationally slow and impractical as a management tool but did demonstrate that the equation could be solved for flow entering relatively dry soils.

Several methods of dealing with the sediment hydraulic characteristics were tested.

Annotation: Discusses some of the complexities of computer modeling of unsaturated water flow, particularly for conditions where sharp wetting fronts occur in dry soils. An appendix by G. S. Campbell provides an analysis of non-isothermal flow and makes estimates of relative magnitudes of vapor and liquid fluxes under conditions typical of the Hanford site.

22. Routson, R. C. and K. R. Fecht. 1979. Soil (Sediment) Properties of Twelve Hanford Wells With Geologic Interpretation. RHO-LD-82, Rockwell Hanford Operations.

ABSTRACT

Laboratory soil (sediment) properties were determined for twelve study wells from an area south of the Hanford 200 West Area. Properties measured included 1) mechanical analysis; 2) porosity; 3) $CaCO_3$ content; 4) moisture content at 0.33, 1.5, and 15 bars water potential; 5) field moisture content; 6) cation exchange capacity; and 7) bulk density. Geologic, stratigraphic cross sections were prepared using the above data and previously published data for the the study area.

Annotation: The data from the study wells, representing over 500 samples, indicated that the soils in this study area are extremely coarse textured (less than 3% clay content, with an average moisture content of 2.1% [grams H_2O/gram soil) x 100] at the 15 bar water potential). The reported field moisture data average 1.5%, with only 22 of 528 samples having more than 3% moisture. The authors indicate that moisture losses during sampling, storage and subsampling were unknown and may account for the low moisture content values (more than half the samples had reported moisture contents less than 1%).

9 3 1 2 4 5 2 1 5 0 0

23. Sisson, J. B., and A. H. Lu. 1984. Field Calibration of Computer Models for Application to Buried Liquid Discharges: A Status Report. RHO-ST-46P, Rockwell Hanford Operations, Richland, Washington.

ABSTRACT

A field experiment for calibrating computer models was conducted. Data from the experiment were compared directly to the output of a computer model. The model inputs were estimated from in situ information and computer forecasts of moisture movement were made. The forecasts were biased at some points in the system. The bias could be removed by using improved estimates of the parameters. The model correctly forecast that horizontal movement would dominate in situ wetting patterns.

Annotation: Presents an extensive data set consisting of neutron probe and gamma probe logs from a set of observation wells surrounding a shallow injection well located in the 200 East Area. Water and tracers (Sr-85 and Cs-134) were injected at a 5.7 m depth. Radial and vertical migration of moisture and tracers were measured in the observation wells with time. Natural soil layering caused significant lateral spreading of the injected water with time. Model results were based on soil hydraulic properties taken from soils some distance (5 mi) from the test site. The general shape of the water plume and the injection pulse effect on water content could be simulated when layered soil properties were incorporated into the model. Initial soil moisture contents in the subsurface sediments ranged from 4 to 8 vol%. After 4.17 x 10^4 L (11,000 gal) were injected, water contents ranged from 4 to 26 vol% and lateral spreading occurred over a radius of 9 m.

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